1. Preface
2. The Chemistry of Life
    1. The Study of Life
        1. Introduction
        2. The Science of Biology
    2. The Chemical Foundation of Life
        1. Introduction
        2. Atoms, Isotopes, Ions, and Molecules: The Building Blocks
3. The Cell
    1. Cell Structure
        1. Introduction
        2. Studying Cells
4. Measurements and the Metric System

Preface

Biology is designed for multi-semester biology courses for science majors. It is grounded on an evolutionary basis and includes exciting features that highlight careers in the biological sciences and everyday applications of the concepts at hand. To meet the needs of today's instructors and students, some content has been strategically condensed while maintaining the overall scope and coverage of traditional texts for this course. Instructors can customize the book, adapting it to the approach that works best in their classroom. Biology also includes an innovative art program that incorporates critical thinking and clicker questions to help students understand—and apply—key concepts.

Welcome to *Biology 2e* (2nd edition), an OpenStax resource. This textbook was written to increase student access to high-quality learning materials, maintaining highest standards of academic rigor at little to no cost.

## About OpenStax

OpenStax is a nonprofit based at Rice University, and it's our mission to improve student access to education. Our first openly licensed college textbook was published in 2012, and our library has since scaled to over 25 books for college and AP® courses used by hundreds of thousands of students. OpenStax Tutor, our low-cost personalized learning tool, is being used in college courses throughout the country. Through our partnerships with philanthropic foundations and our alliance with other educational resource organizations, OpenStax is breaking down the most common barriers to learning and empowering students and instructors to succeed.

## About OpenStax resources

### Customization

*Biology 2e* is licensed under a Creative Commons Attribution 4.0 International (CC BY) license, which means that you can distribute, remix, and build upon the content, as long as you provide attribution to OpenStax and its content contributors.

Because our books are openly licensed, you are free to use the entire book or pick and choose the sections that are most relevant to the needs of your course. Feel free to remix the content by assigning your students certain chapters and sections in your syllabus, in the order that you prefer. You can even provide a direct link in your syllabus to the sections in the web view of your book.

Instructors also have the option of creating a customized version of their OpenStax book. The custom version can be made available to students in low-cost print or digital form through their campus bookstore. Visit the Instructor Resources section of your book page on OpenStax.org for more information.

### Errata

All OpenStax textbooks undergo a rigorous review process. However, like any professional-grade textbook, errors sometimes occur. Since our books are web based, we can make updates periodically when deemed pedagogically necessary. If you have a correction to suggest, submit it through the link on your book page on OpenStax.org. Subject matter experts review all errata suggestions. OpenStax is committed to remaining transparent about all updates, so you will also find a list of past errata changes on your book page on OpenStax.org.

### Format

You can access this textbook for free in web view or PDF through OpenStax.org, and for a low cost in print.

## About *Biology 2e*

*Biology 2e* (2nd edition) is designed to cover the scope and sequence requirements of a typical two-semester biology course for science majors. The text provides comprehensive coverage of foundational research and

core biology concepts through an evolutionary lens. *Biology* includes rich features that engage students in scientific inquiry, highlight careers in the biological sciences, and offer everyday applications. The book also includes various types of practice and homework questions that help students understand — and apply — key concepts.

The 2nd edition has been revised to incorporate clearer, more current, and more dynamic explanations, while maintaining the same organization as the first edition. Art and illustrations have been substantially improved, and the textbook features additional assessments and related resources.

## Coverage and scope

*Biology* was one of the first textbooks published by OpenStax and has been used by hundreds of faculty and thousands of students since 2012. We mined our adopters' extensive and helpful feedback to identify the most significant revision needs while maintaining the organization that many instructors had incorporated into their courses. Specific surveys, focus groups, and pre-revision reviews, as well as data from our OpenStax Tutor users, all aided in planning the revision.

The result is a book that thoroughly treats biology's foundational concepts while adding current and meaningful coverage in specific areas. *Biology 2e* retains its manageable scope and contains ample features to draw learners into the discipline.

Structurally, the textbook remains similar to the first edition, with no chapter reorganization and very targeted changes at the section level (mostly in biodiversity).

**Unit 1: The Chemistry of Life.** Our opening unit introduces students to the sciences, including the scientific method and the fundamental concepts of chemistry and physics that provide a framework within which learners comprehend biological processes.
**Unit 2: The Cell.** Students will gain solid understanding of the structures, functions, and processes of the most basic unit of life: the

cell.

**Unit 3: Genetics.** Our comprehensive genetics unit takes learners from the earliest experiments that revealed the basis of genetics through the intricacies of DNA to current applications in the emerging studies of biotechnology and genomics.

**Unit 4: Evolutionary Processes.** The core concepts of evolution are discussed in this unit with examples illustrating evolutionary processes. Additionally, the evolutionary basis of biology reappears throughout the textbook in general discussion and is reinforced through special call-out features highlighting specific evolution-based topics.

**Unit 5: Biological Diversity.** The diversity of life is explored with detailed study of various organisms and discussion of emerging phylogenetic relationships. This unit moves from viruses to living organisms like bacteria, discusses the organisms formerly grouped as protists, and devotes multiple chapters to plant and animal life.

**Unit 6: Plant Structure and Function.** Our plant unit thoroughly covers the fundamental knowledge of plant life essential to an introductory biology course.

**Unit 7: Animal Structure and Function.** An introduction to the form and function of the animal body is followed by chapters on specific body systems and processes. This unit touches on the biology of all organisms while maintaining an engaging focus on human anatomy and physiology that helps students connect to the topics.

**Unit 8: Ecology.** Ecological concepts are broadly covered in this unit, with features highlighting localized, real-world issues of conservation and biodiversity.

## Changes to the Second Edition

OpenStax only undertakes second editions when significant modifications to the text are necessary. In the case of *Biology 2e*, user feedback indicated that we needed to focus on a few key areas, which we have done in the following ways:

**Content revisions for clarity, accuracy, and currency.** The revision plan varied by chapter based on need. About twenty chapters were wholly revised with significant updates to conceptual coverage, research-informed data, and clearer language. In about fifteen other chapters, the revisions focused mostly on readability and clearer language with fewer conceptual and factual changes.

**Additional end-of-chapter questions.** The authors added new assessments to nearly every chapter, including both review and critical thinking questions. The additions total over 350 new items.

**Art and illustrations.** Under the guidance of the authors and expert scientific illustrators, especially those well versed in creating accessible art, the OpenStax team made changes to most of the art in *Biology*. You will find examples in the section below. The revisions fall into the following categories:

- Revisions for accuracy
- Redesigns for greater understanding and impact
- Recoloring art for overall consistency

**Accessibility improvements.** As with all OpenStax books, the first edition of *Biology* was created with a focus on accessibility. We have emphasized and improved that approach in the second edition.

- To accommodate users of specific assistive technologies, all alternative text was reviewed and revised for comprehensiveness and clarity.
- Many illustrations were revised to improve the color contrast, which is important for some visually impaired students.
- Overall, the OpenStax platform has been continually upgraded to improve accessibility.

A transition guide will be available on OpenStax.org to highlight the specific chapter-level changes to the second edition.

## Pedagogical foundation

The pedagogical choices, chapter arrangements, and learning objective fulfillment were developed and vetted with the feedback of another one hundred reviewers, who thoroughly read the material and offered detailed critical commentary.

**Evolution Connection** features uphold the importance of evolution to all biological study through discussions like “The Evolution of Metabolic Pathways” and “Algae and Evolutionary Paths to Photosynthesis.”
**Scientific Method Connection** call-outs walk students through actual or thought experiments that elucidate the steps of the scientific process as applied to the topic. Features include “Determining the Time Spent in Cell Cycle Stages” and “Testing the Hypothesis of Independent Assortment.”
**Career Connection** features present information on a variety of careers in the biological sciences, introducing students to the educational requirements and day-to-day work life of a variety of professions, such as microbiologist, ecologist, neurologist, and forensic scientist.
**Everyday Connection** features tie biological concepts to emerging issues and discuss science in terms of everyday life. Topics include “Chesapeake Bay” and “Can Snail Venom Be Used as a Pharmacological Pain Killer?”

## Art and animations that engage

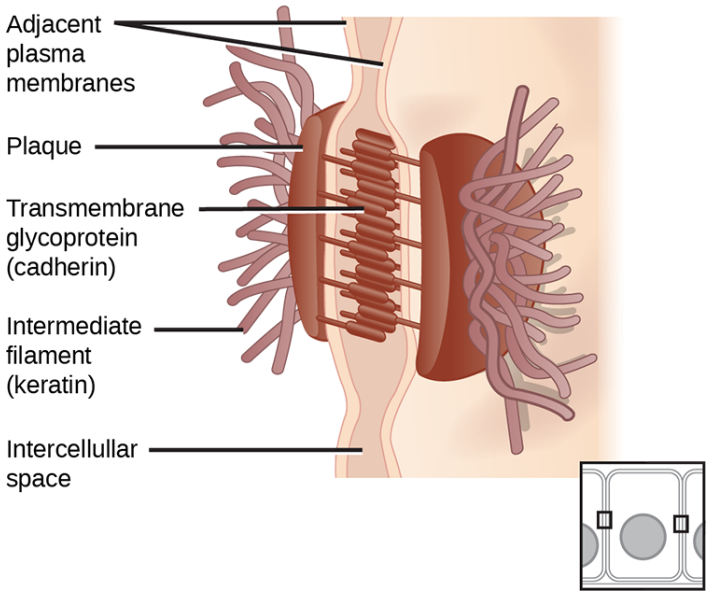
Our art program takes a straightforward approach designed to help students learn the concepts of biology through simple, effective illustrations, photos, and micrographs. Biology 2e also incorporates links to relevant animations and interactive exercises that help bring biology to life for students.

**Visual Connection** features call out core figures in each chapter for student study. Questions about key figures, including clicker questions that can be used in the classroom, engage students’ critical thinking and analytical abilities to ensure their genuine understanding.

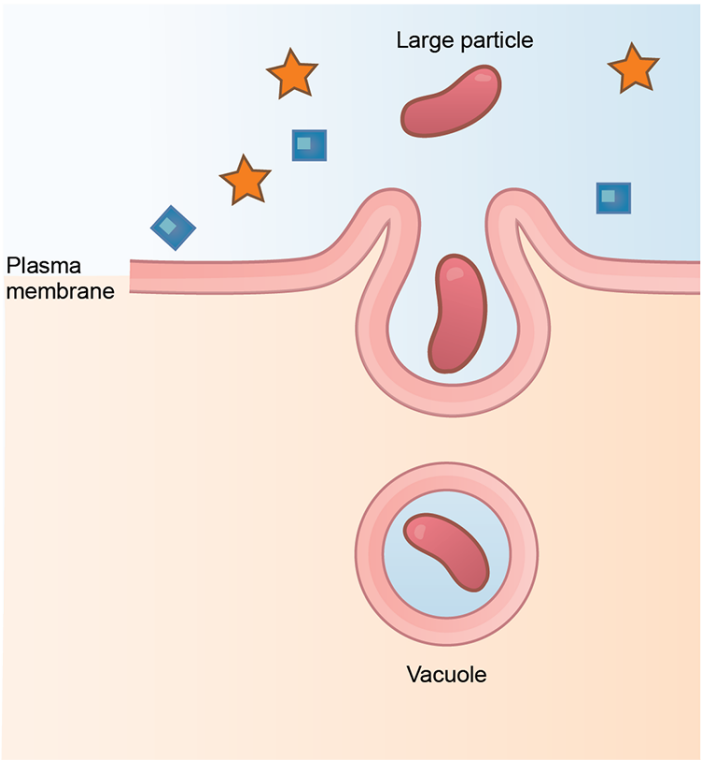
**Link to Learning** features direct students to online interactive exercises and animations to add a fuller context and examples to core content.

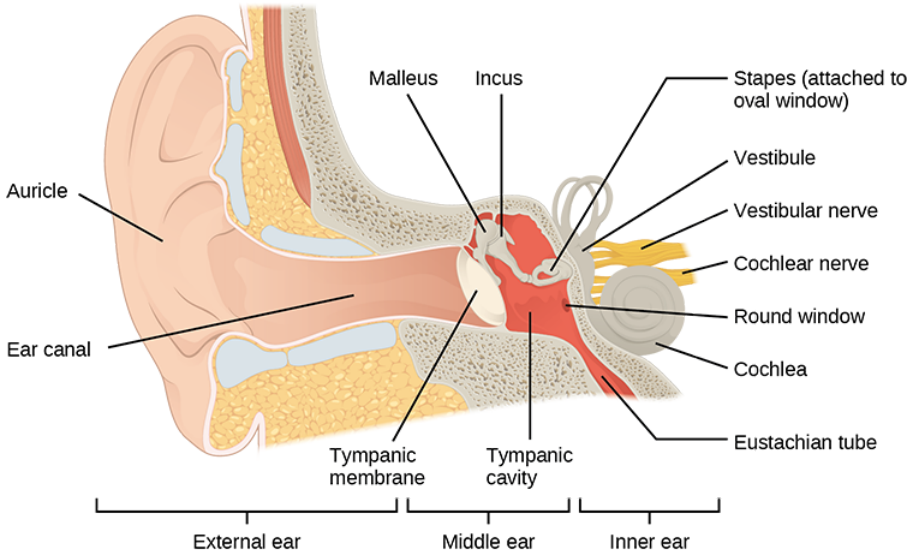
Below are a few examples of the revised art for *Biology 2e*:

**Desmosome**




Phagocytosis






## Additional resources

### Student and instructor resources

We've compiled additional resources for both students and instructors, including Getting Started Guides, an instructor solution guide, and PowerPoint lecture slides. Instructor resources require a verified instructor account, which you can apply for when you log in or create your account on OpenStax.org. Take advantage of these resources to supplement your OpenStax book.

### Community Hubs

OpenStax partners with the Institute for the Study of Knowledge Management in Education (ISKME) to offer Community Hubs on OER Commons – a platform for instructors to share community-created resources that support OpenStax books, free of charge. Through our Community Hubs, instructors can upload their own materials or download resources to use in their own courses, including additional ancillaries, teaching material, multimedia, and relevant course content. We encourage instructors to join the hubs for the subjects most relevant to your teaching

and research as an opportunity both to enrich your courses and to engage with other faculty.

To reach the Community Hubs, visit www.oercommons.org/hubs/OpenStax.

### Technology partners

As allies in making high-quality learning materials accessible, our technology partners offer optional low-cost tools that are integrated with OpenStax books. To access the technology options for your text, visit your book page on OpenStax.org.

## About the authors

### Second edition authors and reviewers

**Senior Contributing Authors**
Mary Ann Clark, Texas Wesleyan University
Jung Choi, Georgia Institute of Technology
Matthew Douglas, Grand Rapids Community College

**Reviewers**
Kathleen Berlyn, Baltimore City Community College
Bridgett Brinton, Armstrong State University
Jennifer Chase, Northwest Nazarene University
Amy Hoffman, Grayson County College
Olga Kopp, Utah Valley University
Jennifer Larson, Capital University
Jason Locklin, Austin Community College
Hongmei Ma, American University
Melissa Masse, Tulsa Community College
Shannon McDermott, Central Virginia Community College
Bryan Monesson-Olson, University of Massachusetts Amherst
Amber Reece, California State University Fresno
Monique Reed, Texas A&M University

Jeffrey Roberts, American River College
Matthew Smith, North Dakota State University
Dawn Wankowski, Cardinal Stritch University

**First edition authors and reviewers**

**Senior Contributing Authors**
Yael Avissar (Cell Biology), Rhode Island College
Jung Choi (Genetics), Georgia Institute of Technology
Jean DeSaix (Evolution), University of North Carolina at Chapel Hill
Vladimir Jurukovski (Animal Physiology), Suffolk County Community College
Robert Wise (Plant Biology), University of Wisconsin, Oshkosh
Connie Rye (General Content Lead), East Mississippi Community College

**Contributing Authors and Reviewers**
Julie Adams, Aurora University
Summer Allen, Brown University
James Bader, Case Western Reserve University
David Bailey, St. Norbert College
Mark Belk, Brigham Young University
Nancy Boury, Iowa State University
Lisa Bonneau, Metropolitan Community College – Blue River
Graciela Brelles-Marino, California State University Pomona
Mark Browning, Purdue University
Sue Chaplin, University of St. Thomas
George Cline, Jacksonville State University
Deb Cook, Georgia Gwinnett College
Diane Day, Clayton State University
Frank Dirrigl, The University of Texas Pan American
Waneene Dorsey, Grambling State University
Nick Downey, University of Wisconsin La Crosse
Rick Duhrkopf, Baylor University
Kristy Duran, Adams State University
Stan Eisen, Christian Brothers University
Brent Ewers, University of Wyoming

Myriam Feldman, Lake Washington Institute of Technology
Michael Fine, Virginia Commonwealth University
Linda Flora, Delaware County Community College
Thomas Freeland, Walsh University
David Grisé, Texas A & M University – Corpus Christi
Andrea Hazard, SUNY Cortland
Michael Hedrick, University of North Texas
Linda Hensel, Mercer University
Mark Kopeny, University of Virginia
Norman Johnson, University of Massachusetts Amherst
Grace Lasker, Lake Washington Institute of Technology; Walden University
Sandy Latourelle, SUNY Plattsburgh
Theo Light, Shippensburg University
Clark Lindgren, Grinnell College
James Malcolm, University of Redlands
Mark Meade, Jacksonville State University
Richard Merritt, Houston Community College
James Mickle, North Carolina State University
Jasleen Mishra, Houston Community College
Dudley Moon, Albany College of Pharmacy and Health Sciences
Shobhana Natarajan, Brookhaven College
Jonas Okeagu, Fayetteville State University
Diana Oliveras, University of Colorado Boulder
John Peters, College of Charleston
Joel Piperberg, Millersville University
Johanna Porter-Kelley, Winston-Salem State University
Robyn Puffenbarger, Bridgewater College
Dennis Revie, California Lutheran University
Ann Rushing, Baylor University
Sangha Saha, City College of Chicago
Edward Saiff, Ramapo College of New Jersey
Brian Shmaefsky, Lone Star College System
Robert Sizemore, Alcorn State University
Marc Smith, Sinclair Community College
Frederick Spiegel, University of Arkansas
Frederick Sproull, La Roche College
Bob Sullivan, Marist College

Mark Sutherland, Hendrix College
Toure Thompson, Alabama A&M University
Scott Thomson, University of Wisconsin – Parkside
Allison van de Meene, University of Melbourne
Mary White, Southeastern Louisiana University
Steven Wilt, Bellarmine University
James Wise, Hampton University
Renna Wolfe
Virginia Young, Mercer University
Leslie Zeman, University of Washington
Daniel Zurek, Pittsburg State University
Shobhana Natarajan, Alcon Laboratories, Inc.

Introduction
class="introduction"

This NASA image is a composite of several satellite-based views of Earth. To make the whole-Earth image, NASA scientists combine observations of different parts of the planet. (credit: NASA/GSFC/NOAA/USGS)

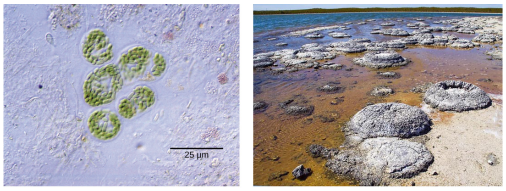
Viewed from space, Earth offers no clues about the diversity of life forms that reside there. Scientists believe that the first forms of life on Earth were microorganisms that existed for billions of years in the ocean before plants and animals appeared. The mammals, birds, and flowers so familiar to us are all relatively recent, originating 130 to 250 million years ago. The earliest representatives of the genus *Homo*, to which we belong, have

inhabited this planet for only the last 2.5 million years, and only in the last 300,000 years have humans started looking like we do today.

The Science of Biology

By the end of this section, you will be able to do the following:

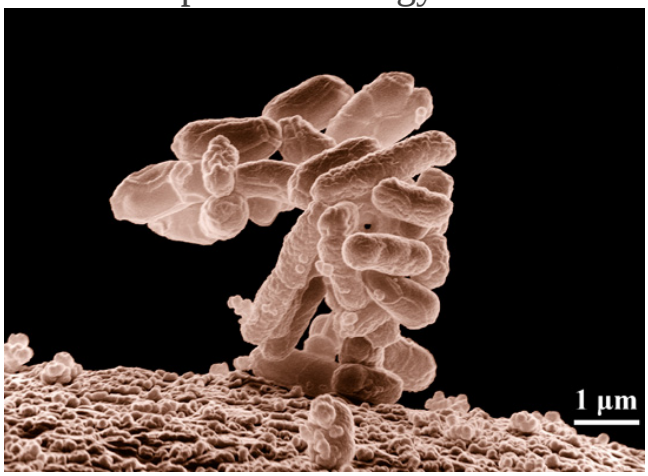
- Identify the shared characteristics of the natural sciences
- Summarize the steps of the scientific method
- Compare inductive reasoning with deductive reasoning
- Describe the goals of basic science and applied science




Formerly called blue-green algae, these (a) cyanobacteria, magnified 300x under a light microscope, are some of Earth's oldest life forms. These (b) stromatolites along the shores of Lake Thetis in Western Australia are ancient structures formed by layering cyanobacteria in shallow waters. (credit a: modification of work by NASA; credit b: modification of work by Ruth Ellison; scale-bar data from Matt Russell)

What is biology? In simple terms, **biology** is the study of living organisms and their interactions with one another and their environments. This is a very broad definition because the scope of biology is vast. Biologists may

study anything from the microscopic or submicroscopic view of a cell to ecosystems and the whole living planet ([link]). Listening to the daily news, you will quickly realize how many aspects of biology we discuss every day. For example, recent news topics include *Escherichia coli* ([link]) outbreaks in spinach and *Salmonella* contamination in peanut butter. Other subjects include efforts toward finding a cure for AIDS, Alzheimer's disease, and cancer. On a global scale, many researchers are committed to finding ways to protect the planet, solve environmental issues, and reduce the effects of climate change. All of these diverse endeavors are related to different facets of the discipline of biology.




*Escherichia coli* (*E. coli*) bacteria, in this scanning electron micrograph, are normal residents of our digestive tracts that aid in absorbing vitamin K and other nutrients. However, virulent strains are sometimes responsible for disease outbreaks. (credit: Eric Erbe, digital colorization by Christopher Pooley, both of USDA, ARS, EMU)

## The Process of Science

Biology is a science, but what exactly is science? What does the study of biology share with other scientific disciplines? We can define **science** (from the Latin *scientia*, meaning “knowledge”) as knowledge that covers general truths or the operation of general laws, especially when acquired and tested by the scientific method. It becomes clear from this definition that applying scientific method plays a major role in science. The **scientific method** is a method of research with defined steps that include experiments and careful observation.

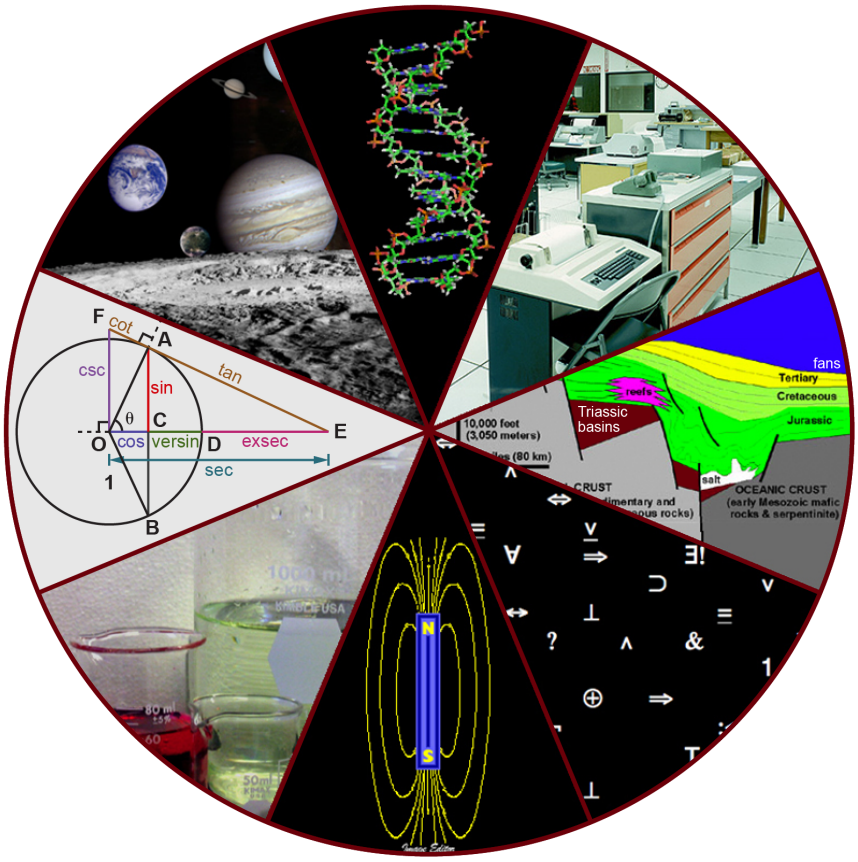
We will examine scientific method steps in detail later, but one of the most important aspects of this method is the testing of hypotheses by means of repeatable experiments. A **hypothesis** is a suggested explanation for an event, which one can test. Although using the scientific method is inherent to science, it is inadequate in determining what science is. This is because it is relatively easy to apply the scientific method to disciplines such as physics and chemistry, but when it comes to disciplines like archaeology, psychology, and geology, the scientific method becomes less applicable as repeating experiments becomes more difficult.

These areas of study are still sciences, however. Consider archaeology—even though one cannot perform repeatable experiments, hypotheses may still be supported. For instance, an archaeologist can hypothesize that an ancient culture existed based on finding a piece of pottery. He or she could make further hypotheses about various characteristics of this culture, which could be correct or false through continued support or contradictions from other findings. A hypothesis may become a verified theory. A **theory** is a tested and confirmed explanation for observations or phenomena. Therefore, we may be better off to define science as fields of study that attempt to comprehend the nature of the universe.

## Natural Sciences

What would you expect to see in a museum of natural sciences? Frogs? Plants? Dinosaur skeletons? Exhibits about how the brain functions? A planetarium? Gems and minerals? Maybe all of the above? Science includes such diverse fields as astronomy, biology, computer sciences, geology,

logic, physics, chemistry, and mathematics ([link]). However, scientists consider those fields of science related to the physical world and its phenomena and processes **natural sciences**. Thus, a museum of natural sciences might contain any of the items listed above.




The diversity of scientific fields includes astronomy, biology, computer science, geology, logic, physics, chemistry, mathematics, and many other fields. (credit: “Image Editor”/Flickr)

There is no complete agreement when it comes to defining what the natural sciences include, however. For some experts, the natural sciences are astronomy, biology, chemistry, earth science, and physics. Other scholars

choose to divide natural sciences into **life sciences**, which study living things and include biology, and **physical sciences**, which study nonliving matter and include astronomy, geology, physics, and chemistry. Some disciplines such as biophysics and biochemistry build on both life and physical sciences and are interdisciplinary. Some refer to natural sciences as "hard science" because they rely on the use of quantitative data. Social sciences that study society and human behavior are more likely to use qualitative assessments to drive investigations and findings.

Not surprisingly, the natural science of biology has many branches or subdisciplines. Cell biologists study cell structure and function, while biologists who study anatomy investigate the structure of an entire organism. Those biologists studying physiology, however, focus on the internal functioning of an organism. Some areas of biology focus on only particular types of living things. For example, botanists explore plants, while zoologists specialize in animals.

## Scientific Reasoning

One thing is common to all forms of science: an ultimate goal "to know." Curiosity and inquiry are the driving forces for the development of science. Scientists seek to understand the world and the way it operates. To do this, they use two methods of logical thinking: inductive reasoning and deductive reasoning.

**Inductive reasoning** is a form of logical thinking that uses related observations to arrive at a general conclusion. This type of reasoning is common in descriptive science. A life scientist such as a biologist makes observations and records them. These data can be qualitative or quantitative, and one can supplement the raw data with drawings, pictures, photos, or videos. From many observations, the scientist can infer conclusions (inductions) based on evidence. Inductive reasoning involves formulating generalizations inferred from careful observation and analyzing a large amount of data. Brain studies provide an example. In this type of research, scientists observe many live brains while people are engaged in a specific activity, such as viewing images of food. The scientist then predicts

the part of the brain that “lights up” during this activity to be the part controlling the response to the selected stimulus, in this case, images of food. Excess absorption of radioactive sugar derivatives by active areas of the brain causes the various areas to "light up". Scientists use a scanner to observe the resultant increase in radioactivity. Then, researchers can stimulate that part of the brain to see if similar responses result.

Deductive reasoning or deduction is the type of logic used in hypothesis-based science. In deductive reason, the pattern of thinking moves in the opposite direction as compared to inductive reasoning. **Deductive reasoning** is a form of logical thinking that uses a general principle or law to forecast specific results. From those general principles, a scientist can extrapolate and predict the specific results that would be valid as long as the general principles are valid. Studies in climate change can illustrate this type of reasoning. For example, scientists may predict that if the climate becomes warmer in a particular region, then the distribution of plants and animals should change.

Both types of logical thinking are related to the two main pathways of scientific study: descriptive science and hypothesis-based science. **Descriptive (or discovery) science**, which is usually inductive, aims to observe, explore, and discover, while **hypothesis-based science**, which is usually deductive, begins with a specific question or problem and a potential answer or solution that one can test. The boundary between these two forms of study is often blurred, and most scientific endeavors combine both approaches. The fuzzy boundary becomes apparent when thinking about how easily observation can lead to specific questions. For example, a gentleman in the 1940s observed that the burr seeds that stuck to his clothes and his dog’s fur had a tiny hook structure. On closer inspection, he discovered that the burrs’ gripping device was more reliable than a zipper. He eventually experimented to find the best material that acted similar, and produced the hook-and-loop fastener popularly known today as Velcro. Descriptive science and hypothesis-based science are in continuous dialogue.

## The Scientific Method

Biologists study the living world by posing questions about it and seeking science-based responses. Known as scientific method, this approach is common to other sciences as well. The scientific method was used even in ancient times, but England's Sir Francis Bacon (1561–1626) first documented it ([link]). He set up inductive methods for scientific inquiry. The scientific method is not used only by biologists; researchers from almost all fields of study can apply it as a logical, rational problem-solving method.

Historians credit Sir Francis Bacon (1561–1626) as the first to define the scientific method. (credit: Paul van Somer)

The scientific process typically starts with an observation (often a problem to solve) that leads to a question. Let's think about a simple problem that starts with an observation and apply the scientific method to solve the problem. One Monday morning, a student arrives at class and quickly discovers that the classroom is too warm. That is an observation that also describes a problem: the classroom is too warm. The student then asks a question: "Why is the classroom so warm?"

## Proposing a Hypothesis

Recall that a hypothesis is a suggested explanation that one can test. To solve a problem, one can propose several hypotheses. For example, one hypothesis might be, "The classroom is warm because no one turned on the air conditioning." However, there could be other responses to the question, and therefore one may propose other hypotheses. A second hypothesis might be, "The classroom is warm because there is a power failure, and so the air conditioning doesn't work."

Once one has selected a hypothesis, the student can make a prediction. A prediction is similar to a hypothesis but it typically has the format "If . . . then . . . ." For example, the prediction for the first hypothesis might be, "*If* the student turns on the air conditioning, *then* the classroom will no longer be too warm."

## Testing a Hypothesis

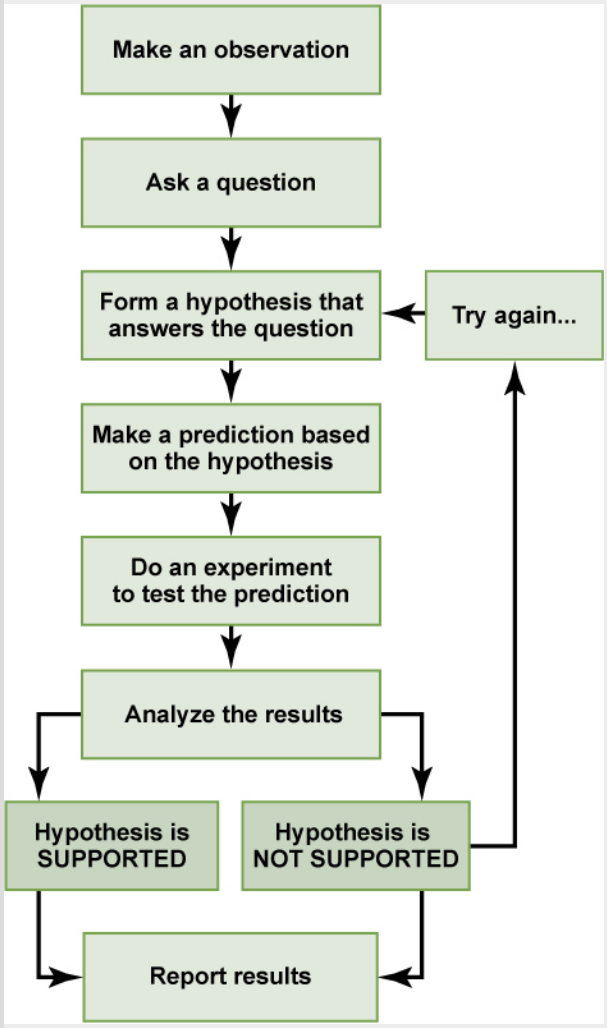
A valid hypothesis must be testable. It should also be **falsifiable**, meaning that experimental results can disprove it. Importantly, science does not claim to "prove" anything because scientific understandings are always subject to modification with further information. This step—openness to disproving ideas—is what distinguishes sciences from non-sciences. The presence of the supernatural, for instance, is neither testable nor falsifiable. To test a hypothesis, a researcher will conduct one or more experiments designed to eliminate one or more of the hypotheses. Each experiment will

have one or more variables and one or more controls. A **variable** is any part of the experiment that can vary or change during the experiment. The **control group** contains every feature of the experimental group except it is not given the manipulation that the researcher hypothesizes. Therefore, if the experimental group's results differ from the control group, the difference must be due to the hypothesized manipulation, rather than some outside factor. Look for the variables and controls in the examples that follow. To test the first hypothesis, the student would find out if the air conditioning is on. If the air conditioning is turned on but does not work, there should be another reason, and the student should reject this hypothesis. To test the second hypothesis, the student could check if the lights in the classroom are functional. If so, there is no power failure and the student should reject this hypothesis. The students should test each hypothesis by carrying out appropriate experiments. Be aware that rejecting one hypothesis does not determine whether or not one can accept the other hypotheses. It simply eliminates one hypothesis that is not valid ([link]). Using the scientific method, the student rejects the hypotheses that are inconsistent with experimental data.

While this “warm classroom” example is based on observational results, other hypotheses and experiments might have clearer controls. For instance, a student might attend class on Monday and realize she had difficulty concentrating on the lecture. One observation to explain this occurrence might be, “When I eat breakfast before class, I am better able to pay attention.” The student could then design an experiment with a control to test this hypothesis.

In hypothesis-based science, researchers predict specific results from a general premise. We call this type of reasoning deductive reasoning: deduction proceeds from the general to the particular. However, the reverse of the process is also possible: sometimes, scientists reach a general conclusion from a number of specific observations. We call this type of reasoning inductive reasoning, and it proceeds from the particular to the general. Researchers often use inductive and deductive reasoning in tandem to advance scientific knowledge ([link]).

**Note:**
Visual Connection

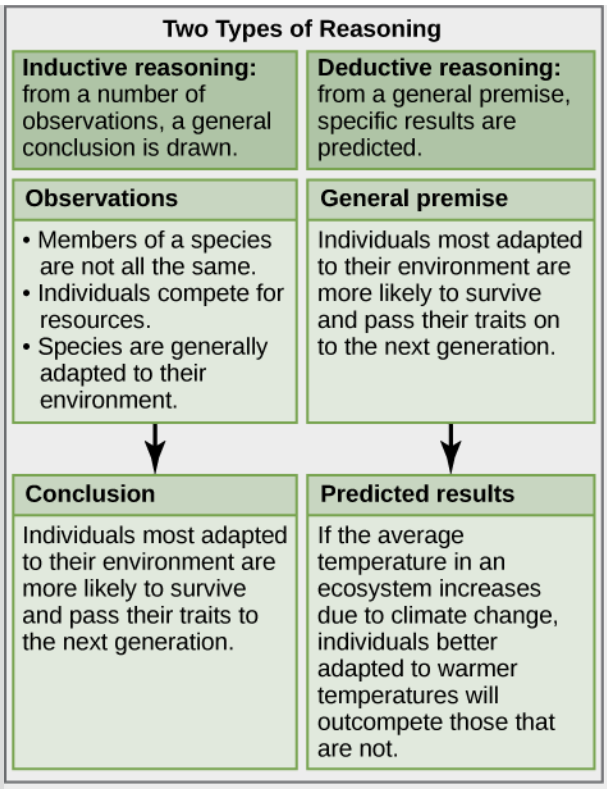

Make an observation
Ask a question
Form a hypothesis that answers the question
Try again...
Make a prediction based on the hypothesis
Do an experiment to test the prediction
Analyze the results
Hypothesis is SUPPORTED
Hypothesis is NOT SUPPORTED
Report results

The scientific method consists of a series of well-defined steps. If a hypothesis is not supported by experimental data, one can propose a new hypothesis.

In the example below, the scientific method is used to solve an everyday problem. Match the scientific method steps (numbered items) with the process of solving the everyday problem (lettered items). Based on the results of the experiment, is the hypothesis correct? If it is incorrect, propose some alternative hypotheses.

| | |
|---|---|
| 1. Observation | a. There is something wrong with the electrical outlet. |
| 2. Question | b. If something is wrong with the outlet, my coffeemaker also won’t work when plugged into it. |
| 3. Hypothesis (answer) | c. My toaster doesn’t toast my bread. |
| 4. Prediction | d. I plug my coffee maker into the outlet. |
| 5. Experiment | e. My coffeemaker works. |
| 6. Result | f. Why doesn’t my toaster work? |

**Note:**
Visual Connection


Two Types of Reasoning
Inductive reasoning: from a number of observations, a general conclusion is drawn.
Deductive reasoning: from a general premise, specific results are predicted.
Observations
• Members of a species are not all the same.
• Individuals compete for resources.
• Species are generally adapted to their environment.
General premise
Individuals most adapted to their environment are more likely to survive and pass their traits on to the next generation.
Conclusion
Individuals most adapted to their environment are more likely to survive and pass their traits to the next generation.
Predicted results
If the average temperature in an ecosystem increases due to climate change, individuals better adapted to warmer temperatures will outcompete those that are not.

Scientists use two types of reasoning, inductive and deductive reasoning, to advance scientific knowledge. As is the case in this example, the conclusion from inductive reasoning can often become the premise for deductive reasoning.

Decide if each of the following is an example of inductive or deductive reasoning.

1. All flying birds and insects have wings. Birds and insects flap their wings as they move through the air. Therefore, wings enable flight.
2. Insects generally survive mild winters better than harsh ones. Therefore, insect pests will become more problematic if global temperatures increase.

3. Chromosomes, the carriers of DNA, are distributed evenly between the daughter cells during cell division. Therefore, each daughter cell will have the same chromosome set as the mother cell.
4. Animals as diverse as humans, insects, and wolves all exhibit social behavior. Therefore, social behavior must have an evolutionary advantage.

The scientific method may seem too rigid and structured. It is important to keep in mind that, although scientists often follow this sequence, there is flexibility. Sometimes an experiment leads to conclusions that favor a change in approach. Often, an experiment brings entirely new scientific questions to the puzzle. Many times, science does not operate in a linear fashion. Instead, scientists continually draw inferences and make generalizations, finding patterns as their research proceeds. Scientific reasoning is more complex than the scientific method alone suggests. Notice, too, that we can apply the scientific method to solving problems that aren't necessarily scientific in nature.

## Two Types of Science: Basic Science and Applied Science

The scientific community has been debating for the last few decades about the value of different types of science. Is it valuable to pursue science for the sake of simply gaining knowledge, or does scientific knowledge only have worth if we can apply it to solving a specific problem or to bettering our lives? This question focuses on the differences between two types of science: basic science and applied science.

**Basic science** or "pure" science seeks to expand knowledge regardless of the short-term application of that knowledge. It is not focused on developing a product or a service of immediate public or commercial value. The immediate goal of basic science is knowledge for knowledge's sake, although this does not mean that, in the end, it may not result in a practical application.

In contrast, **applied science** or “technology,” aims to use science to solve real-world problems, making it possible, for example, to improve a crop yield, find a cure for a particular disease, or save animals threatened by a natural disaster ([link]). In applied science, the problem is usually defined for the researcher.

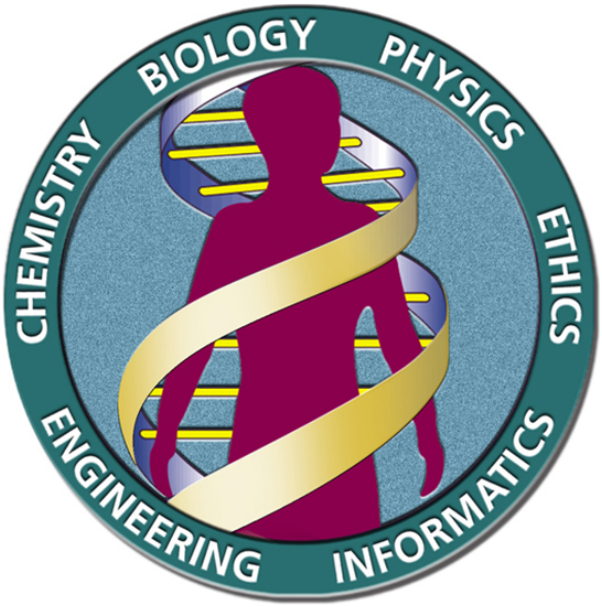
After Hurricane Irma struck the Caribbean and Florida in 2017, thousands of baby squirrels like this one were thrown from their nests. Thanks to applied science, scientists knew how to rehabilitate the squirrel. (credit: audreyjm529, Flickr)

Some individuals may perceive applied science as “useful” and basic science as “useless.” A question these people might pose to a scientist advocating knowledge acquisition would be, “What for?” However, a careful look at the history of science reveals that basic knowledge has resulted in many remarkable applications of great value. Many scientists think that a basic understanding of science is necessary before researchers

develop an application therefore, applied science relies on the results that researchers generate through basic science. Other scientists think that it is time to move on from basic science in order to find solutions to actual problems. Both approaches are valid. It is true that there are problems that demand immediate attention; however, scientists would find few solutions without the help of the wide knowledge foundation that basic science generates.

One example of how basic and applied science can work together to solve practical problems occurred after the discovery of DNA structure led to an understanding of the molecular mechanisms governing DNA replication. DNA strands, unique in every human, are in our cells, where they provide the instructions necessary for life. When DNA replicates, it produces new copies of itself, shortly before a cell divides. Understanding DNA replication mechanisms enabled scientists to develop laboratory techniques that researchers now use to identify genetic diseases, pinpoint individuals who were at a crime scene, and determine paternity. Without basic science, it is unlikely that applied science would exist.

Another example of the link between basic and applied research is the Human Genome Project, a study in which researchers analyzed and mapped each human chromosome to determine the precise sequence of DNA subunits and each gene's exact location. (The gene is the basic unit of heredity. An individual’s complete collection of genes is his or her genome.) Researchers have studied other less complex organisms as part of this project in order to gain a better understanding of human chromosomes. The Human Genome Project ([link]) relied on basic research with simple organisms and, later, with the human genome. An important end goal eventually became using the data for applied research, seeking cures and early diagnoses for genetically related diseases.




The Human Genome Project was a 13-year collaborative effort among researchers working in several different science fields. Researchers completed the project, which sequenced the entire human genome, in 2003. (credit: the U.S. Department of Energy Genome Programs (http://genomics.energy.gov)

While scientists usually carefully plan research efforts in both basic science and applied science, note that some discoveries are made by **serendipity**, that is, by means of a fortunate accident or a lucky surprise. Scottish biologist Alexander Fleming discovered penicillin when he accidentally left a petri dish of *Staphylococcus* bacteria open. An unwanted mold grew on the dish, killing the bacteria. Fleming's curiosity to investigate the reason behind the bacterial death, followed by his experiments, led to the discovery of the antibiotic penicillin, which is produced by the fungus *Penicillium*.

Even in the highly organized world of science, luck—when combined with an observant, curious mind—can lead to unexpected breakthroughs.

## Reporting Scientific Work

Whether scientific research is basic science or applied science, scientists must share their findings in order for other researchers to expand and build upon their discoveries. Collaboration with other scientists—when planning, conducting, and analyzing results—are all important for scientific research. For this reason, important aspects of a scientist's work are communicating with peers and disseminating results to peers. Scientists can share results by presenting them at a scientific meeting or conference, but this approach can reach only the select few who are present. Instead, most scientists present their results in peer-reviewed manuscripts that are published in scientific journals. **Peer-reviewed manuscripts** are scientific papers that a scientist's colleagues or peers review. These colleagues are qualified individuals, often experts in the same research area, who judge whether or not the scientist's work is suitable for publication. The process of peer review helps to ensure that the research in a scientific paper or grant proposal is original, significant, logical, and thorough. Grant proposals, which are requests for research funding, are also subject to peer review. Scientists publish their work so other scientists can reproduce their experiments under similar or different conditions to expand on the findings. The experimental results must be consistent with the findings of other scientists.

A scientific paper is very different from creative writing. Although creativity is required to design experiments, there are fixed guidelines when it comes to presenting scientific results. First, scientific writing must be brief, concise, and accurate. A scientific paper needs to be succinct but detailed enough to allow peers to reproduce the experiments.

The scientific paper consists of several specific sections—introduction, materials and methods, results, and discussion. This structure is sometimes called the "IMRaD" format. There are usually acknowledgment and reference sections as well as an **abstract** (a concise summary) at the beginning of the paper. There might be additional sections depending on the

type of paper and the journal where it will be published. For example, some review papers require an outline.

The **introduction** starts with brief, but broad, background information about what is known in the field. A good introduction also gives the rationale of the work. It justifies the work carried out and also briefly mentions the end of the paper, where the researcher will present the hypothesis or research question driving the research. The introduction refers to the published scientific work of others and therefore requires citations following the style of the journal. Using the work or ideas of others without proper citation is **plagiarism**.

The **materials and methods** section includes a complete and accurate description of the substances the researchers use, and the method and techniques they use to gather data. The description should be thorough enough to allow another researcher to repeat the experiment and obtain similar results, but it does not have to be verbose. This section will also include information on how the researchers made measurements and the types of calculations and statistical analyses they used to examine raw data. Although the materials and methods section gives an accurate description of the experiments, it does not discuss them.

Some journals require a results section followed by a discussion section, but it is more common to combine both. If the journal does not allow combining both sections, the **results** section simply narrates the findings without any further interpretation. The researchers present results with tables or graphs, but they do not present duplicate information. In the **discussion** section, the researchers will interpret the results, describe how variables may be related, and attempt to explain the observations. It is indispensable to conduct an extensive literature search to put the results in the context of previously published scientific research. Therefore, researchers include proper citations in this section as well.

Finally, the **conclusion** section summarizes the importance of the experimental findings. While the scientific paper almost certainly answers one or more scientific questions that the researchers stated, any good research should lead to more questions. Therefore, a well-done scientific

paper allows the researchers and others to continue and expand on the findings.

**Review articles** do not follow the IMRAD format because they do not present original scientific findings, or primary literature. Instead, they summarize and comment on findings that were published as primary literature and typically include extensive reference sections.

## Section Summary

Biology is the science that studies living organisms and their interactions with one another and their environments. Science attempts to describe and understand the nature of the universe in whole or in part by rational means. Science has many fields. Those fields related to the physical world and its phenomena are natural sciences.

Science can be basic or applied. The main goal of basic science is to expand knowledge without any expectation of short-term practical application of that knowledge. The primary goal of applied research, however, is to solve practical problems.

Science uses two types of logical reasoning. Inductive reasoning uses particular results to produce general scientific principles. Deductive reasoning is a form of logical thinking that predicts results by applying general principles. The common thread throughout scientific research is using the scientific method, a step-based process that consists of making observations, defining a problem, posing hypotheses, testing these hypotheses, and drawing one or more conclusions. The testing uses proper controls. Scientists present their results in peer-reviewed scientific papers published in scientific journals. A scientific research paper consists of several well-defined sections: introduction, materials and methods, results, and, finally, a concluding discussion. Review papers summarize the conducted research in a particular field over a period of time.

## Visual Connection Questions

**Exercise:**

**Problem:**

[link] In the example below, the scientific method is used to solve an everyday problem. Match the scientific method steps (numbered items) with the process of solving the everyday problem (lettered items). Based on the results of the experiment, is the hypothesis correct? If it is incorrect, propose some alternative hypotheses.

| | |
|---|---|
| 1. Observation | a. There is something wrong with the electrical outlet. |
| 2. Question | b. If something is wrong with the outlet, my coffeemaker also won't work when plugged into it. |
| 3. Hypothesis (answer) | c. My toaster doesn't toast my bread. |
| 4. Prediction | d. I plug my coffee maker into the outlet. |
| 5. Experiment | e. My coffeemaker works. |
| 6. Result | f. Why doesn't my toaster work? |

---

**Solution:**

[link] 1: C; 2: F; 3: A; 4: B; 5: D; 6: E. The original hypothesis is incorrect, as the coffeemaker works when plugged into the outlet.

Alternative hypotheses include that the toaster might be broken or that the toaster wasn't turned on.

**Exercise:**

**Problem:**

[link] Decide if each of the following is an example of inductive or deductive reasoning.

1. All flying birds and insects have wings. Birds and insects flap their wings as they move through the air. Therefore, wings enable flight.
2. Insects generally survive mild winters better than harsh ones. Therefore, insect pests will become more problematic if global temperatures increase.
3. Chromosomes, the carriers of DNA, separate into daughter cells during cell division. Therefore, each daughter cell will have the same chromosome set as the mother cell.
4. Animals as diverse as humans, insects, and wolves all exhibit social behavior. Therefore, social behavior must have an evolutionary advantage.

---

**Solution:**

[link] 1: inductive; 2: deductive; 3: deductive; 4: inductive.

## Review Questions

**Exercise:**

**Problem:** The first forms of life on Earth were _____.

a. plants
b. microorganisms
c. birds
d. dinosaurs

**Solution:**

B

**Exercise:**

**Problem:**

A suggested and testable explanation for an event is called a _____.

a. hypothesis
b. variable
c. theory
d. control

---

**Solution:**

A

**Exercise:**

**Problem:**

Which of the following sciences is not considered a natural science?

a. biology
b. astronomy
c. physics
d. computer science

---

**Solution:**

D

**Exercise:**

**Problem:**

The type of logical thinking that uses related observations to arrive at a general conclusion is called _____.

a. deductive reasoning
b. the scientific method
c. hypothesis-based science
d. inductive reasoning

---

**Solution:**

D

**Exercise:**

**Problem:**

The process of _____ helps to ensure that a scientist's research is original, significant, logical, and thorough.

a. publication
b. public speaking
c. peer review
d. the scientific method

---

**Solution:**

C

**Exercise:**

**Problem:**

A person notices that her houseplants that are regularly exposed to music seem to grow more quickly than those in rooms with no music. As a result, she determines that plants grow better when exposed to music. This example most closely resembles which type of reasoning?

a. inductive reasoning
b. deductive reasoning
c. neither, because no hypothesis was made
d. both inductive and deductive reasoning

---

**Solution:**

A

## Critical Thinking Questions

**Exercise:**

**Problem:**

Although the scientific method is used by most of the sciences, it can also be applied to everyday situations. Think about a problem that you may have at home, at school, or with your car, and apply the scientific method to solve it.

---

**Solution:**

Answers will vary, but should apply the steps of the scientific method. One possibility could be a car which doesn't start. The hypothesis could be that the car doesn't start because the battery is dead. The experiment would be to change the battery or to charge the battery and then check whether the car starts or not. If it starts, the problem was due to the battery, and the hypothesis is accepted.

**Exercise:**

**Problem:**

Give an example of how applied science has had a direct effect on your daily life.

---

**Solution:**

Answers will vary. One example of how applied science has had a direct effect on daily life is the presence of vaccines. Vaccines to prevent diseases such polio, measles, tetanus, and even influenza affect daily life by contributing to individual and societal health.

**Exercise:**

**Problem:**

Name two topics that are likely to be studied by biologists, and two areas of scientific study that would fall outside the realm of biology.

---

**Solution:**

Answers will vary. Topics that fall inside the area of biological study include how diseases affect human bodies, how pollution impacts a species' habitat, and how plants respond to their environments. Topics that fall outside of biology (the "study of life") include how metamorphic rock is formed and how planetary orbits function.

**Exercise:**

**Problem:**

Thinking about the topic of cancer, write a basic science question and an applied science question that a researcher interested in this topic might ask.

---

**Solution:**

Answers will vary. Basic science: What evolutionary purpose might cancer serve? Applied science: What strategies might be found to prevent cancer from reproducing at the cellular level?

## Glossary

abstract
: opening section of a scientific paper that summarizes the research and conclusions

applied science
: form of science that aims to solve real-world problems

basic science
: science that seeks to expand knowledge and understanding regardless of the short-term application of that knowledge

biology
: the study of living organisms and their interactions with one another and their environments

conclusion
: section of a scientific paper that summarizes the importance of the experimental findings

control
: part of an experiment that does not change during the experiment

deductive reasoning
: form of logical thinking that uses a general inclusive statement to forecast specific results

descriptive science
: (also, discovery science) form of science that aims to observe, explore, and investigate

discussion
: section of a scientific paper in which the author interprets experimental results, describes how variables may be related, and attempts to explain the phenomenon in question

falsifiable
: able to be disproven by experimental results

hypothesis
: suggested explanation for an observation, which one can test

hypothesis-based science

form of science that begins with a specific question and potential testable answers

inductive reasoning
: form of logical thinking that uses related observations to arrive at a general conclusion

introduction
: opening section of a scientific paper, which provides background information about what was known in the field prior to the research reported in the paper

life science
: field of science, such as biology, that studies living things

materials and methods
: section of a scientific paper that includes a complete description of the substances, methods, and techniques that the researchers used to gather data

natural science
: field of science that is related to the physical world and its phenomena and processes

peer-reviewed manuscript
: scientific paper that a scientist's colleagues review who are experts in the field of study

physical science
: field of science, such as geology, astronomy, physics, and chemistry, that studies nonliving matter

plagiarism
: using other people's work or ideas without proper citation, creating the false impression that those are the author's original ideas

results

section of a scientific paper in which the author narrates the experimental findings and presents relevant figures, pictures, diagrams, graphs, and tables, without any further interpretation

review article
: paper that summarizes and comments on findings that were published as primary literature

science
: knowledge that covers general truths or the operation of general laws, especially when acquired and tested by the scientific method

scientific method
: method of research with defined steps that include observation, formulation of a hypothesis, testing, and confirming or falsifying the hypothesis

serendipity
: fortunate accident or a lucky surprise

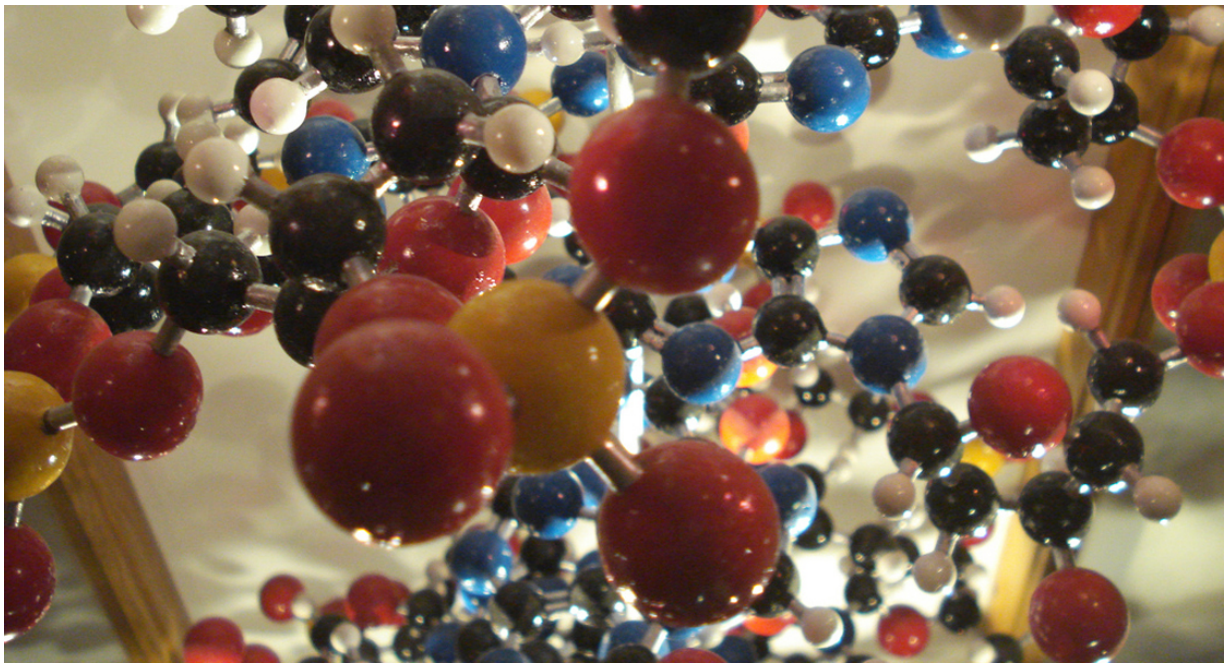
theory
: tested and confirmed explanation for observations or phenomena

variable
: part of an experiment that the experimenter can vary or change

Introduction
class="introduction"

Atoms are the building blocks of molecules in the universe—air, soil, water, rocks . . . and also the cells of all living organisms. In this model of an organic molecule, the atoms of carbon (black), hydrogen (white), nitrogen (blue), oxygen (red), and sulfur (yellow) are in proportional atomic size. The silver rods indicate chemical bonds.

(credit: modification of work by Christian Guthier)



Elements in various combinations comprise all matter, including living things. Some of the most abundant elements in living organisms include carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorus. These form the nucleic acids, proteins, carbohydrates, and lipids that are the fundamental components of living matter. Biologists must understand these important building blocks and the unique structures of the atoms that comprise molecules, allowing for cells, tissues, organ systems, and entire organisms to form.

All biological processes follow the laws of physics and chemistry, so in order to understand how biological systems work, it is important to understand the underlying physics and chemistry. For example, the flow of blood within the circulatory system follows the laws of physics that regulate the modes of fluid flow. The breakdown of the large, complex molecules of food into smaller molecules—and the conversion of these to release energy

to be stored in adenosine triphosphate (ATP)—is a series of chemical reactions that follow chemical laws. The properties of water and the formation of hydrogen bonds are key to understanding living processes. Recognizing the properties of acids and bases is important, for example, to our understanding of the digestive process. Therefore, the fundamentals of physics and chemistry are important for gaining insight into biological processes.

## Atoms, Isotopes, Ions, and Molecules: The Building Blocks

By the end of this section, you will be able to do the following:

- Define matter and elements
- Describe the interrelationship between protons, neutrons, and electrons
- Compare the ways in which electrons can be donated or shared between atoms
- Explain the ways in which naturally occurring elements combine to create molecules, cells, tissues, organ systems, and organisms

At its most fundamental level, life is made up of matter. **Matter** is any substance that occupies space and has mass. **Elements** are unique forms of matter with specific chemical and physical properties that cannot break down into smaller substances by ordinary chemical reactions. There are 118 elements, but only 98 occur naturally. The remaining elements are unstable and require scientists to synthesize them in laboratories.

Each element is designated by its chemical symbol, which is a single capital letter or, when the first letter is already "taken" by another element, a combination of two letters. Some elements follow the English term for the element, such as C for carbon and Ca for calcium. Other elements' chemical symbols derive from their Latin names. For example, the symbol for sodium is Na, referring to *natrium*, the Latin word for sodium.

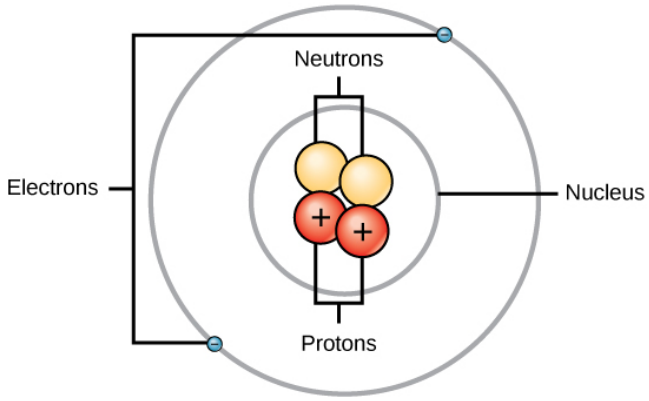
The four elements common to all living organisms are oxygen (O), carbon (C), hydrogen (H), and nitrogen (N). In the nonliving world, elements are found in different proportions, and some elements common to living organisms are relatively rare on the earth as a whole, as [link] shows. For example, the atmosphere is rich in nitrogen and oxygen but contains little carbon and hydrogen, while the earth's crust, although it contains oxygen and a small amount of hydrogen, has little nitrogen and carbon. In spite of their differences in abundance, all elements and the chemical reactions between them obey the same chemical and physical laws regardless of whether they are a part of the living or nonliving world.

| Approximate Percentage of Elements in Living Organisms (Humans) Compared to the Nonliving World | | | |
|---|---|---|---|
| **Element** | **Life (Humans)** | **Atmosphere** | **Earth's Crust** |
| Oxygen (O) | 65% | 21% | 46% |
| Carbon (C) | 18% | trace | trace |
| Hydrogen (H) | 10% | trace | 0.1% |
| Nitrogen (N) | 3% | 78% | trace |

## The Structure of the Atom

To understand how elements come together, we must first discuss the element's smallest component or building block, the atom. An **atom** is the smallest unit of matter that retains all of the element's chemical properties. For example, one gold atom has all of the properties of gold in that it is a solid metal at room temperature. A gold coin is simply a very large number of gold atoms molded into the shape of a coin and contains small amounts of other elements known as impurities. We cannot break down gold atoms into anything smaller while still retaining the properties of gold.

An atom is composed of two regions: the **nucleus**, which is in the atom's center and contains protons and neutrons. The atom's outermost region holds its electrons in orbit around the nucleus, as [link] illustrates. Atoms contain protons, electrons, and neutrons, among other subatomic particles. The only exception is hydrogen (H), which is made of one proton and one electron with no neutrons.




Elements, such as helium, depicted here, are made up of atoms. Atoms are made up of protons and neutrons located within the nucleus, with electrons in orbitals surrounding the nucleus.

Protons and neutrons have approximately the same mass, about $1.67 \times 10^{-24}$ grams. Scientists arbitrarily define this amount of mass as one atomic mass unit (amu) or one Dalton, as [link] shows. Although similar in mass, protons and neutrons differ in their electric charge. A **proton** is positively charged; whereas, a **neutron** is uncharged. Therefore, the number of neutrons in an atom contributes significantly to its mass, but not to its charge. **Electrons** are much smaller in mass than protons, weighing only $9.11 \times 10^{-28}$ grams, or about 1/1800 of an atomic mass unit. Hence, they do not contribute much to an element's overall atomic mass. Therefore, when considering atomic mass, it is customary to ignore the mass of any electrons and calculate the atom's mass based on the number of protons and neutrons alone. Although not significant contributors to mass, electrons do contribute greatly to the atom's charge, as each electron has a negative charge equal to the proton's positive charge. In uncharged, neutral atoms, the number of electrons orbiting the nucleus is equal to the number of protons inside the nucleus. In these atoms, the positive and negative charges cancel each other out, leading to an atom with no net charge.

Accounting for the sizes of protons, neutrons, and electrons, most of the atom's volume—greater than 99 percent—is empty space. With all this empty space, one might ask why so-called solid objects do not just pass through one another. The reason they do not is that the electrons that surround all atoms are negatively charged and negative charges repel each other.

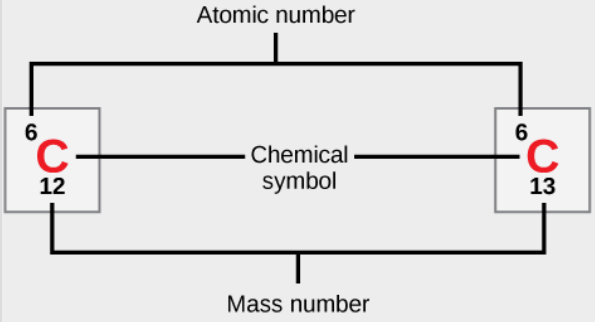
| **Protons, Neutrons, and Electrons** | | | |
|---|---|---|---|
| | **Charge** | **Mass (amu)** | **Location** |
| Proton | +1 | 1 | nucleus |
| Neutron | 0 | 1 | nucleus |
| Electron | –1 | 0 | orbitals |

## Atomic Number and Mass

Atoms of each element contain a characteristic number of protons and electrons. The number of protons determines an element’s **atomic number**, which scientists use to distinguish one element from another. The number of neutrons is variable, resulting in isotopes, which are different forms of the same atom that vary only in the number of neutrons they possess. Together, the number of protons and neutrons determine an element’s **mass number**, as [link] illustrates. Note that we disregard the small contribution of mass from electrons in calculating the mass number. We can use this approximation of mass to easily calculate how many neutrons an element has by simply subtracting the number of protons from the mass number. Since an element’s isotopes will have slightly different mass numbers, scientists also determine the **atomic mass**, which is the calculated mean of

the mass number for its naturally occurring isotopes. Often, the resulting number contains a fraction. For example, the atomic mass of chlorine (Cl) is 35.45 because chlorine is composed of several isotopes, some (the majority) with atomic mass 35 (17 protons and 18 neutrons) and some with atomic mass 37 (17 protons and 20 neutrons).

**Note:**
Visual Connection




Carbon has an atomic number of six, and two stable isotopes with mass numbers of twelve and thirteen, respectively. Its relative atomic mass is 12.011

How many neutrons do carbon-12 and carbon-13 have, respectively?

## Isotopes

**Isotopes** are different forms of an element that have the same number of protons but a different number of neutrons. Some elements—such as carbon, potassium, and uranium—have naturally occurring isotopes. Carbon-12 contains six protons, six neutrons, and six electrons; therefore, it has a mass number of 12 (six protons and six neutrons). Carbon-14 contains six protons, eight neutrons, and six electrons; its atomic mass is 14 (six

protons and eight neutrons). These two alternate forms of carbon are isotopes. Some isotopes may emit neutrons, protons, and electrons, and attain a more stable atomic configuration (lower level of potential energy); these are radioactive isotopes, or **radioisotopes**. Radioactive decay (carbon-14 decaying to eventually become nitrogen-14) describes the energy loss that occurs when an unstable atom's nucleus releases radiation.

**Note:**
Evolution Connection
**Carbon Dating**
Carbon is normally present in the atmosphere in the form of gaseous compounds like carbon dioxide and methane. Carbon-14 ($^{14}C$) is a naturally occurring radioisotope that is created in the atmosphere from atmospheric $^{14}N$ (nitrogen) by the addition of a neutron and the loss of a proton because of cosmic rays. This is a continuous process, so more $^{14}C$ is always being created. As a living organism incorporates $^{14}C$ initially as carbon dioxide fixed in the process of photosynthesis, the relative amount of $^{14}C$ in its body is equal to the concentration of $^{14}C$ in the atmosphere. When an organism dies, it is no longer ingesting $^{14}C$, so the ratio between $^{14}C$ and $^{12}C$ will decline as $^{14}C$ decays gradually to $^{14}N$ by a process called beta decay—electrons or positrons emission. This decay emits energy in a slow process.
After approximately 5,730 years, half of the starting concentration of $^{14}C$ will convert back to $^{14}N$. We call the time it takes for half of the original concentration of an isotope to decay back to its more stable form its half-life. Because the half-life of $^{14}C$ is long, scientists use it to date formerly living objects such as old bones or wood. Comparing the ratio of the $^{14}C$ concentration in an object to the amount of $^{14}C$ in the atmosphere, scientists can determine the amount of the isotope that has not yet decayed. On the basis of this amount, [link] shows that we can calculate the age of the material, such as the pygmy mammoth, with accuracy if it is not much older than about 50,000 years. Other elements have isotopes with different half lives. For example, $^{40}K$ (potassium-40) has a half-life of 1.25 billion years, and $^{235}U$ (Uranium 235) has a half-life of about 700 million years. Through the use of radiometric dating, scientists can study the age of

fossils or other remains of extinct organisms to understand how organisms have evolved from earlier species.

Scientists can determine the age of carbon-containing remains less than about 50,000 years old, such as this pygmy mammoth, using carbon dating. (credit: Bill Faulkner, NPS)

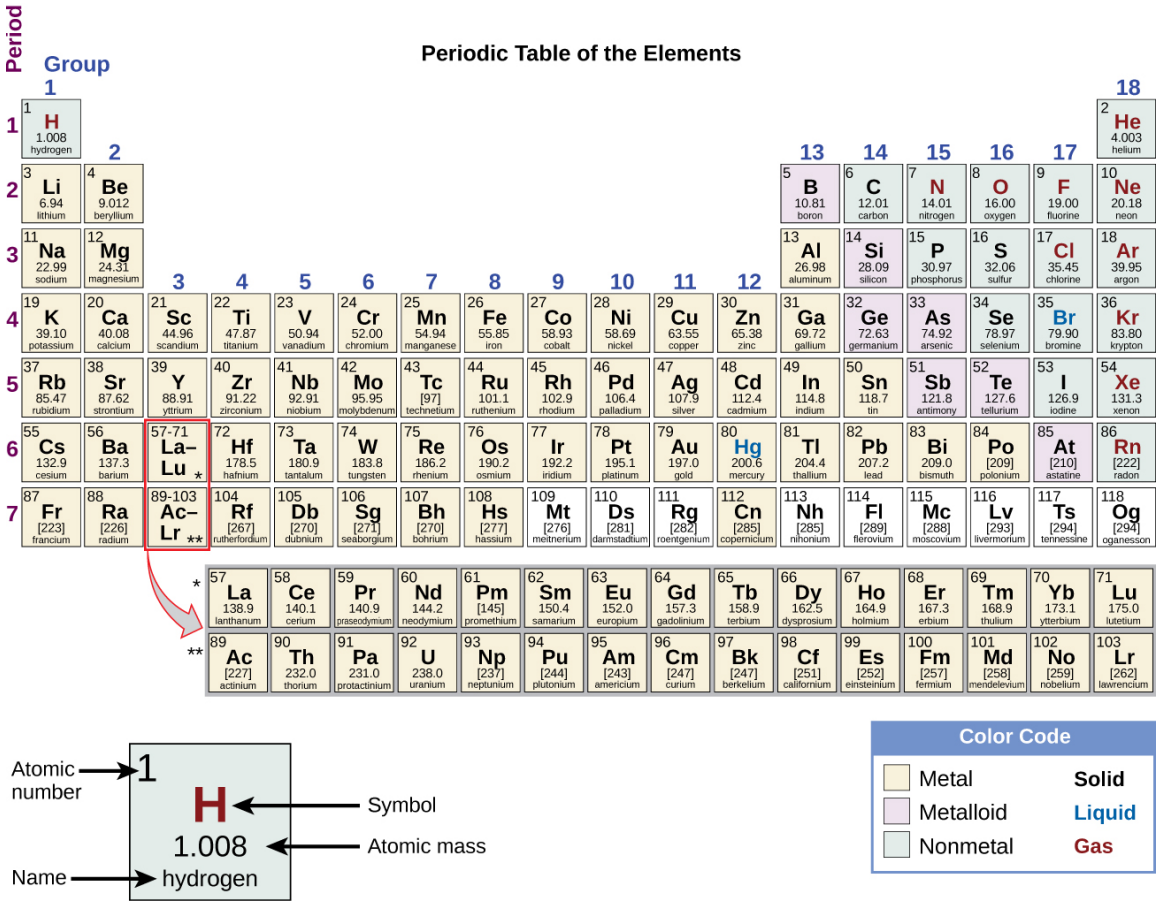
**Note:**
Link to Learning
To learn more about atoms, isotopes, and how to tell one isotope from another, run the simulation.
https://openstax.org/l/atoms_isotopes

## The Periodic Table

The **periodic table** organizes and displays different elements. Devised by Russian chemist Dmitri Mendeleev (1834–1907) in 1869, the table groups

elements that, although unique, share certain chemical properties with other elements. The properties of elements are responsible for their physical state at room temperature: they may be gases, solids, or liquids. Elements also have specific **chemical reactivity**, the ability to combine and to chemically bond with each other.

In the periodic table in [link], the elements are organized and displayed according to their atomic number and are arranged in a series of rows and columns based on shared chemical and physical properties. In addition to providing the atomic number for each element, the periodic table also displays the element's atomic mass. Looking at carbon, for example, its symbol (C) and name appear, as well as its atomic number of six (in the upper left-hand corner) and its atomic mass of 12.11.




The periodic table shows each element's atomic mass and atomic

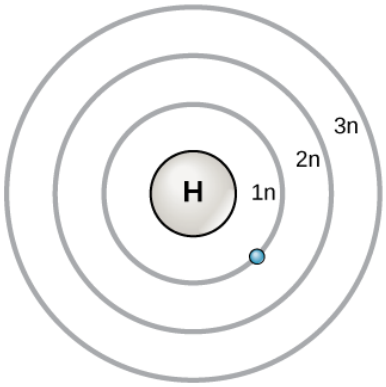
number. The atomic number appears above the symbol for the element and the approximate atomic mass appears below it.

The periodic table groups elements according to chemical properties. Scientists base the differences in chemical reactivity between the elements on the number and spatial distribution of an atom's electrons. Atoms that chemically react and bond to each other form molecules. **Molecules** are simply two or more atoms chemically bonded together. Logically, when two atoms chemically bond to form a molecule, their electrons, which form the outermost region of each atom, come together first as the atoms form a chemical bond.

## Electron Shells and the Bohr Model

Note that there is a connection between the number of protons in an element, the atomic number that distinguishes one element from another, and the number of electrons it has. In all electrically neutral atoms, the number of electrons is the same as the number of protons. Thus, each element, at least when electrically neutral, has a characteristic number of electrons equal to its atomic number.

In 1913, Danish scientist Niels Bohr (1885–1962) developed an early model of the atom. The Bohr model shows the atom as a central nucleus containing protons and neutrons, with the electrons in circular **orbitals** at specific distances from the nucleus, as [link] illustrates. These orbits form electron shells or energy levels, which are a way of visualizing the number of electrons in the outermost shells. These energy levels are designated by a number and the symbol "n." For example, 1n represents the first energy level located closest to the nucleus.



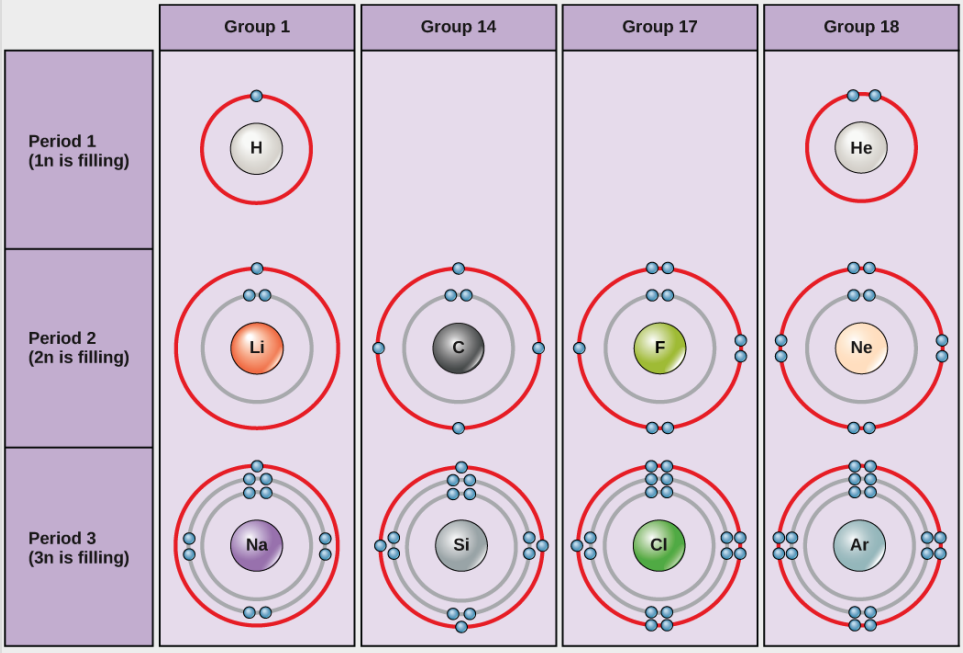

In 1913, Niels Bohrs developed the Bohr model in which electrons exist within principal shells. An electron normally exists in the lowest energy shell available, which is the one closest to the nucleus. Energy from a photon of light can bump it up to a higher energy shell, but this situation is unstable, and the electron quickly decays back to the ground state. In the process, it releases a photon of light.

Electrons fill orbitals in a consistent order: they first fill the orbitals closest to the nucleus, then they continue to fill orbitals of increasing energy further from the nucleus. If there are multiple orbitals of equal energy, they fill with one electron in each energy level before adding a second electron. The electrons of the outermost energy level determine the atom's energetic

stability and its tendency to form chemical bonds with other atoms to form molecules.

Under standard conditions, atoms fill the inner shells first, often resulting in a variable number of electrons in the outermost shell. The innermost shell has a maximum of two electrons but the next two electron shells can each have a maximum of eight electrons. This is known as the **octet rule**, which states, with the exception of the innermost shell, that atoms are more stable energetically when they have eight electrons in their **valence shell**, the outermost electron shell. [link] shows examples of some neutral atoms and their electron configurations. Notice that in [link], helium has a complete outer electron shell, with two electrons filling its first and only shell. Similarly, neon has a complete outer 2n shell containing eight electrons. In contrast, chlorine and sodium have seven and one in their outer shells, respectively, but theoretically they would be more energetically stable if they followed the octet rule and had eight.

**Note:**
Visual Connection




Bohr diagrams indicate how many electrons fill each

principal shell. Group 18 elements (helium, neon, and argon) have a full outer, or valence, shell. A full valence shell is the most stable electron configuration. Elements in other groups have partially filled valence shells and gain or lose electrons to achieve a stable electron configuration.

An atom may give, take, or share electrons with another atom to achieve a full valence shell, the most stable electron configuration. Looking at this figure, how many electrons do elements in group 1 need to lose in order to achieve a stable electron configuration? How many electrons do elements in groups 14 and 17 need to gain to achieve a stable configuration?

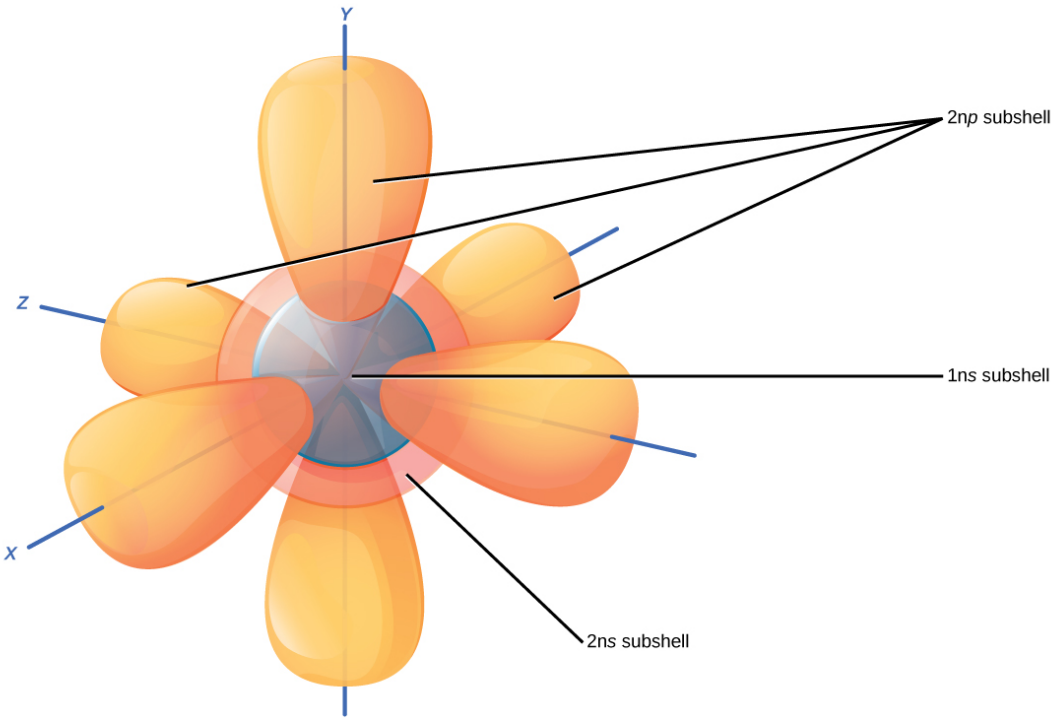
Understanding that the periodic table's organization is based on the total number of protons (and electrons) helps us know how electrons distribute themselves among the shells. The periodic table is arranged in columns and rows based on the number of electrons and their location. Examine more closely some of the elements in the table's far right column in [link]. The group 18 atoms helium (He), neon (Ne), and argon (Ar) all have filled outer electron shells, making it unnecessary for them to share electrons with other atoms to attain stability. They are highly stable as single atoms. Because they are non reactive, scientists coin them **inert** (or **noble gases**). Compare this to the group 1 elements in the left-hand column. These elements, including hydrogen (H), lithium (Li), and sodium (Na), all have one electron in their outermost shells. That means that they can achieve a stable configuration and a filled outer shell by donating or sharing one electron with another atom or a molecule such as water. Hydrogen will donate or share its electron to achieve this configuration, while lithium and sodium will donate their electron to become stable. As a result of losing a negatively charged electron, they become positively charged **ions**. Group 17 elements, including fluorine and chlorine, have seven electrons in their outmost shells, so they tend to fill this shell with an electron from other atoms or molecules, making them negatively charged ions. Group 14 elements, of which carbon is the most important to living systems, have

four electrons in their outer shell allowing them to make several covalent bonds (discussed below) with other atoms. Thus, the periodic table's columns represent the potential shared state of these elements' outer electron shells that is responsible for their similar chemical characteristics.

## Electron Orbitals

Although useful to explain the reactivity and chemical bonding of certain elements, the Bohr model does not accurately reflect how electrons spatially distribute themselves around the nucleus. They do not circle the nucleus like the earth orbits the sun, but we find them in **electron orbitals**. These relatively complex shapes result from the fact that electrons behave not just like particles, but also like waves. Mathematical equations from quantum mechanics, which scientists call wave functions, can predict within a certain level of probability where an electron might be at any given time. Scientists call the area where an electron is most likely to be found its orbital.

Recall that the Bohr model depicts an atom's electron shell configuration. Within each electron shell are subshells, and each subshell has a specified number of orbitals containing electrons. While it is impossible to calculate exactly an electron's location, scientists know that it is most probably located within its orbital path. The letter s, *p*, *d*, and *f* designate the subshells. The *s* subshell is spherical in shape and has one orbital. Principal shell 1n has only a single *s* orbital, which can hold two electrons. Principal shell 2n has one *s* and one *p* subshell, and can hold a total of eight electrons. The *p* subshell has three dumbbell-shaped orbitals, as [link] illustrates. Subshells *d* and *f* have more complex shapes and contain five and seven orbitals, respectively. We do not show these in the illustration. Principal shell 3n has *s*, *p*, and *d* subshells and can hold 18 electrons. Principal shell 4n has *s*, *p*, *d* and *f* orbitals and can hold 32 electrons. Moving away from the nucleus, the number of electrons and orbitals in the energy levels increases. Progressing from one atom to the next in the periodic table, we can determine the electron structure by fitting an extra electron into the next available orbital.




The *s* subshells are shaped like spheres. Both the 1n and 2n principal shells have an *s* orbital, but the size of the sphere is larger in the 2n orbital. Each sphere is a single orbital. Three dumbbell-shaped orbitals comprise *p* subshells. Principal shell 2n has a *p* subshell, but shell 1 does not.

The closest orbital to the nucleus, the 1s orbital, can hold up to two electrons. This orbital is equivalent to the Bohr model's innermost electron shell. Scientists call it the 1*s* orbital because it is spherical around the nucleus. The 1*s* orbital is the closest orbital to the nucleus, and it is always filled first, before any other orbital fills. Hydrogen has one electron; therefore, it occupies only one spot within the 1*s* orbital. We designate this as $1s^1$, where the superscripted 1 refers to the one electron within the 1*s* orbital. Helium has two electrons; therefore, it can completely fill the 1*s* orbital with its two electrons. We designate this as $1s^2$, referring to the two electrons of helium in the 1*s* orbital. On the periodic table [link], hydrogen and helium are the only two elements in the first row (period). This is because they only have electrons in their first shell, the 1*s* orbital. Hydrogen

and helium are the only two elements that have the 1*s* and no other electron orbitals in the electrically neutral state.

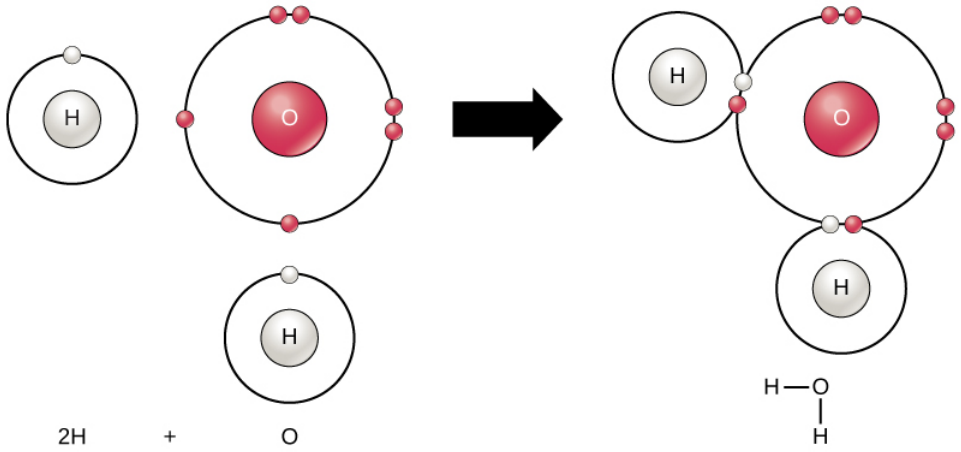
The second electron shell may contain eight electrons. This shell contains another spherical *s* orbital and three “dumbbell” shaped *p* orbitals, each of which can hold two electrons, as [link] shows. After the 1*s* orbital fills, the second electron shell fills, first filling its 2*s* orbital and then its three *p* orbitals. When filling the *p* orbitals, each takes a single electron. Once each *p* orbital has an electron, it may add a second. Lithium (Li) contains three electrons that occupy the first and second shells. Two electrons fill the 1*s* orbital, and the third electron then fills the 2*s* orbital. Its **electron configuration** is $1s^2 2s^1$. Neon (Ne), alternatively, has a total of ten electrons: two are in its innermost 1*s* orbital and eight fill its second shell (two each in the 2*s* and three *p* orbitals). Thus it is an inert gas and energetically stable as a single atom that will rarely form a chemical bond with other atoms. Larger elements have additional orbitals, comprising the third electron shell. While the concepts of electron shells and orbitals are closely related, orbitals provide a more accurate depiction of an atom's electron configuration because the orbital model specifies the different shapes and special orientations of all the places that electrons may occupy.

**Note:**
Link to Learning
Watch this visual animation to see the spatial arrangement of the p and s orbitals.
https://www.openstax.org/l/orbitals

## Chemical Reactions and Molecules

All elements are most stable when their outermost shell is filled with electrons according to the octet rule. This is because it is energetically favorable for atoms to be in that configuration and it makes them stable. However, since not all elements have enough electrons to fill their outermost shells, atoms form **chemical bonds** with other atoms thereby

obtaining the electrons they need to attain a stable electron configuration. When two or more atoms chemically bond with each other, the resultant chemical structure is a molecule. The familiar water molecule, $H_2O$, consists of two hydrogen atoms and one oxygen atom. These bond together to form water, as [link] illustrates. Atoms can form molecules by donating, accepting, or sharing electrons to fill their outer shells.




Two or more atoms may bond with each other to form a molecule. When two hydrogens and an oxygen share electrons via covalent bonds it forms a water molecule.

**Chemical reactions** occur when two or more atoms bond together to form molecules or when bonded atoms break apart. Scientists call the substances used in the beginning of a chemical reaction **reactants** (usually on the left side of a chemical equation), and we call the substances at the end of the reaction **products** (usually on the right side of a chemical equation). We typically draw an arrow between the reactants and products to indicate the chemical reaction's direction. This direction is not always a “one-way street.” To create the water molecule above, the chemical equation would be:

**Equation:**

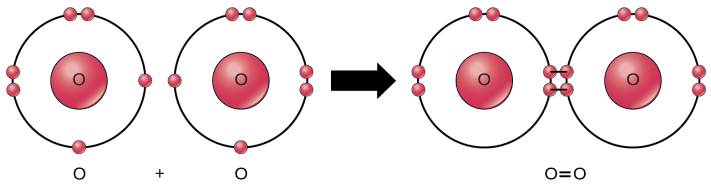
$$2H + O \rightarrow H_2O$$

An example of a simple chemical reaction is breaking down hydrogen peroxide molecules, each of which consists of two hydrogen atoms bonded to two oxygen atoms ($H_2O_2$). The reactant hydrogen peroxide breaks down into water, containing one oxygen atom bound to two hydrogen atoms ($H_2O$), and oxygen, which consists of two bonded oxygen atoms ($O_2$). In the equation below, the reaction includes two hydrogen peroxide molecules and two water molecules. This is an example of a **balanced chemical equation**, wherein each element's number of atoms is the same on each side of the equation. According to the law of conservation of matter, the number of atoms before and after a chemical reaction should be equal, such that no atoms are, under normal circumstances, created or destroyed.

**Equation:**

$$2H_2O_2\,(\text{hydrogen peroxide}) \rightarrow 2H_2O\,(\text{water}) + O_2\,(\text{oxygen})$$

Even though all of the reactants and products of this reaction are molecules (each atom remains bonded to at least one other atom), in this reaction only hydrogen peroxide and water are representatives of **compounds**: they contain atoms of more than one type of element. Molecular oxygen, alternatively, as [link] shows, consists of two doubly bonded oxygen atoms and is not classified as a compound but as a homonuclear molecule.




A double bond joins the oxygen atoms in an $O_2$ molecule.

Some chemical reactions, such as the one above, can proceed in one direction until they expend all the reactants. The equations that describe these reactions contain a unidirectional arrow and are **irreversible**. **Reversible reactions** are those that can go in either direction. In reversible reactions, reactants turn into products, but when the product's concentration goes beyond a certain threshold (characteristic of the particular reaction), some of these products convert back into reactants. At this point, product and reactant designations reverse. This back and forth continues until a certain relative balance between reactants and products occurs—a state called **equilibrium**. A chemical equation with a double headed arrow pointing towards both the reactants and products often denote these reversible reaction situations.

For example, in human blood, excess hydrogen ions ($H^+$) bind to bicarbonate ions ($HCO_3^-$) forming an equilibrium state with carbonic acid ($H_2CO_3$). If we added carbonic acid to this system, some of it would convert to bicarbonate and hydrogen ions.
**Equation:**

$$\mathrm{HCO_3^- + H^+ \leftrightarrow H_2CO_3}$$

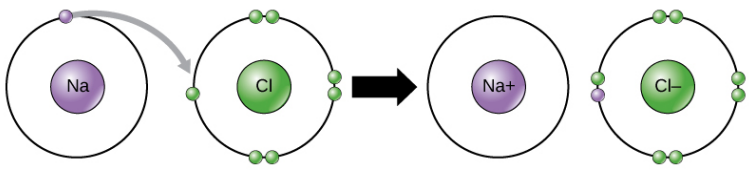
However, biological reactions rarely obtain equilibrium because the concentrations of the reactants or products or both are constantly changing, often with one reaction's product a reactant for another. To return to the example of excess hydrogen ions in the blood, forming carbonic acid will be the reaction's major direction. However, the carbonic acid can also leave the body as carbon dioxide gas (via exhalation) instead of converting back to bicarbonate ion, thus driving the reaction to the right by the **law of mass action**. These reactions are important for maintaining homeostasis in our blood.
**Equation:**

$$\mathrm{HCO_3^- + H^+ \ \leftrightarrow \ H_2CO_3 \ \leftrightarrow \ CO_2 + H_2O}$$

## Ions and Ionic Bonds

Some atoms are more stable when they gain or lose an electron (or possibly two) and form ions. This fills their outermost electron shell and makes them energetically more stable. Because the number of electrons does not equal the number of protons, each ion has a net charge. **Cations** are positive ions that form by losing electrons. Negative ions form by gaining electrons, which we call anions. We designate **anions** by their elemental name and change the ending to "-ide", thus the anion of chlorine is chloride, and the anion of sulfur is sulfide.

Scientists refer to this movement of electrons from one element to another as **electron transfer**. As [link] illustrates, sodium (Na) only has one electron in its outer electron shell. It takes less energy for sodium to donate that one electron than it does to accept seven more electrons to fill the outer shell. If sodium loses an electron, it now has 11 protons, 11 neutrons, and only 10 electrons, leaving it with an overall charge of +1. We now refer to it as a sodium ion. Chlorine (Cl) in its lowest energy state (called the ground state) has seven electrons in its outer shell. Again, it is more energy-efficient for chlorine to gain one electron than to lose seven. Therefore, it tends to gain an electron to create an ion with 17 protons, 17 neutrons, and 18 electrons, giving it a net negative (–1) charge. We now refer to it as a chloride ion. In this example, sodium will donate its one electron to empty its shell, and chlorine will accept that electron to fill its shell. Both ions now satisfy the octet rule and have complete outermost shells. Because the number of electrons is no longer equal to the number of protons, each is now an ion and has a +1 (sodium cation) or –1 (chloride anion) charge. Note that these transactions can normally only take place simultaneously: in order for a sodium atom to lose an electron, it must be in the presence of a suitable recipient like a chlorine atom.




In the formation of an ionic compound, metals lose electrons and nonmetals gain

electrons to achieve an octet.

**Ionic bonds** form between ions with opposite charges. For instance, positively charged sodium ions and negatively charged chloride ions bond together to make crystals of sodium chloride, or table salt, creating a crystalline molecule with zero net charge.

Physiologists refer to certain salts as **electrolytes** (including sodium, potassium, and calcium), ions necessary for nerve impulse conduction, muscle contractions, and water balance. Many sports drinks and dietary supplements provide these ions to replace those lost from the body via sweating during exercise.

## Covalent Bonds and Other Bonds and Interactions

Another way to satisfy the octet rule is by sharing electrons between atoms to form **covalent bonds**. These bonds are stronger and much more common than ionic bonds in the molecules of living organisms. We commonly find covalent bonds in carbon-based organic molecules, such as our DNA and proteins. We also find covalent bonds in inorganic molecules like $H_2O$, $CO_2$, and $O_2$. The bonds may share one, two, or three pairs of electrons, making single, double, and triple bonds, respectively. The more covalent bonds between two atoms, the stronger their connection. Thus, triple bonds are the strongest.

The strength of different levels of covalent bonding is one of the main reasons living organisms have a difficult time in acquiring nitrogen for use in constructing their molecules, even though molecular nitrogen, $N_2$, is the most abundant gas in the atmosphere. Molecular nitrogen consists of two nitrogen atoms triple bonded to each other and, as with all molecules, sharing these three pairs of electrons between the two nitrogen atoms allows for filling their outer electron shells, making the molecule more stable than the individual nitrogen atoms. This strong triple bond makes it difficult for living systems to break apart this nitrogen in order to use it as constituents of proteins and DNA.

Forming water molecules provides an example of covalent bonding. Covalent bonds bind the hydrogen and oxygen atoms that combine to form water molecules as [link] shows. The electron from the hydrogen splits its time between the hydrogen atoms' incomplete outer shell and the oxygen atoms' incomplete outer shell. To completely fill the oxygen's outer shell, which has six electrons but which would be more stable with eight, two electrons (one from each hydrogen atom) are needed: hence, the well-known formula $H_2O$. The two elements share the electrons to fill the outer shell of each, making both elements more stable.

**Note:**
Link to Learning
View this short video to see an animation of ionic and covalent bonding.
https://www.openstax.org/l/ionic_covalent

## Polar Covalent Bonds

There are two types of covalent bonds: polar and nonpolar. In a **polar covalent bond**, [link] shows atoms unequally share the electrons and are attracted more to one nucleus than the other. Because of the unequal electron distribution between the atoms of different elements, a slightly positive ($\delta+$) or slightly negative ($\delta-$) charge develops. This partial charge is an important property of water and accounts for many of its characteristics.

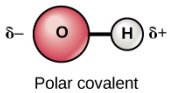
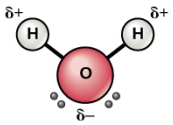
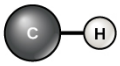
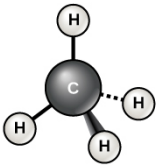
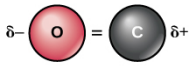
Water is a polar molecule, with the hydrogen atoms acquiring a partial positive charge and the oxygen a partial negative charge. This occurs because the oxygen atom's nucleus is more attractive to the hydrogen atoms' electrons than the hydrogen nucleus is to the oxygen’s electrons. Thus, oxygen has a higher **electronegativity** than hydrogen and the shared electrons spend more time near the oxygen nucleus than the hydrogen atoms' nucleus, giving the oxygen and hydrogen atoms slightly negative and positive charges, respectively. Another way of stating this is that the probability of finding a shared electron near an oxygen nucleus is more

likely than finding it near a hydrogen nucleus. Either way, the atom's relative electronegativity contributes to developing partial charges whenever one element is significantly more electronegative than the other, and the charges that these polar bonds generate may then be used to form hydrogen bonds based on the attraction of opposite partial charges. (Hydrogen bonds, which we discuss in detail below, are weak bonds between slightly positively charged hydrogen atoms to slightly negatively charged atoms in other molecules.) Since macromolecules often have atoms within them that differ in electronegativity, polar bonds are often present in organic molecules.

## Nonpolar Covalent Bonds

**Nonpolar covalent bonds** form between two atoms of the same element or between different elements that share electrons equally. For example, molecular oxygen ($O_2$) is nonpolar because the electrons distribute equally between the two oxygen atoms.

[link] also shows another example of a nonpolar covalent bond—methane ($CH_4$). Carbon has four electrons in its outermost shell and needs four more to fill it. It obtains these four from four hydrogen atoms, each atom providing one, making a stable outer shell of eight electrons. Carbon and hydrogen do not have the same electronegativity but are similar; thus, nonpolar bonds form. The hydrogen atoms each need one electron for their outermost shell, which is filled when it contains two electrons. These elements share the electrons equally among the carbons and the hydrogen atoms, creating a nonpolar covalent molecule.

| | Bond type | Molecular shape | Molecular type |
|---|---|---|---|
| **Water** |  Polar covalent |  Bent | Polar |
| **Methane** |  Nonpolar covalent |  Tetrahedral | Nonpolar |
| **Carbon dioxide** |  Polar covalent | Linear | Nonpolar |

Whether a molecule is polar or nonpolar depends both on bond type and molecular shape. Both water and carbon dioxide have polar covalent bonds, but carbon dioxide is linear, so the partial charges on the molecule cancel each other out.

## Hydrogen Bonds and Van Der Waals Interactions

Ionic and covalent bonds between elements require energy to break. Ionic bonds are not as strong as covalent, which determines their behavior in biological systems. However, not all bonds are ionic or covalent bonds. Weaker bonds can also form between molecules. Two weak bonds that occur frequently are hydrogen bonds and van der Waals interactions. Without these two types of bonds, life as we know it would not exist. Hydrogen bonds provide many of the critical, life-sustaining properties of water and also stabilize the structures of proteins and DNA, the building block of cells.

When polar covalent bonds containing hydrogen form, the hydrogen in that bond has a slightly positive charge because hydrogen’s electron is pulled more strongly toward the other element and away from the hydrogen. Because the hydrogen is slightly positive, it will be attracted to neighboring negative charges. When this happens, a weak interaction occurs between the hydrogen's $\delta^+$ from one molecule and another molecule's $\delta-$ charge on the more electronegative atoms, usually oxygen or nitrogen, or within the same molecule. Scientists call this interaction a **hydrogen bond**. This type of bond is common and occurs regularly between water molecules. Individual hydrogen bonds are weak and easily broken; however, they occur in very large numbers in water and in organic polymers, creating a major force in combination. Hydrogen bonds are also responsible for zipping together the DNA double helix.

Like hydrogen bonds, **van der Waals interactions** are weak attractions or interactions between molecules. Van der Waals attractions can occur between any two or more molecules and are dependent on slight fluctuations of the electron densities, which are not always symmetrical around an atom. For these attractions to happen, the molecules need to be very close to one another. These bonds—along with ionic, covalent, and hydrogen bonds—contribute to the proteins' three-dimensional structure in our cells that is necessary for their proper function.

**Note:**
Career Connection
**Pharmaceutical Chemist**
Pharmaceutical chemists are responsible for developing new drugs and trying to determine the mode of action of both old and new drugs. They are involved in every step of the drug development process. We can find drugs in the natural environment or we can synthesize them in the laboratory. In many cases, chemists chemically change potential drugs from nature chemically in the laboratory to make them safer and more effective, and sometimes synthetic versions of drugs substitute for the version we find in nature.

After a drug's initial discovery or synthesis, the chemist then develops the drug, perhaps chemically altering it, testing it to see if it is toxic, and then designing methods for efficient large-scale production. Then, the process of approving the drug for human use begins. In the United States, the Food and Drug Administration (FDA) handles drug approval. This involves a series of large-scale experiments using human subjects to ensure the drug is not harmful and effectively treats the condition for which it is intended. This process often takes several years and requires the participation of physicians and scientists, in addition to chemists, to complete testing and gain approval.

An example of a drug that was originally discovered in a living organism is Paclitaxel (Taxol), an anti-cancer drug used to treat breast cancer. This drug was discovered in the bark of the pacific yew tree. Another example is aspirin, originally isolated from willow tree bark. Finding drugs often means testing hundreds of samples of plants, fungi, and other forms of life to see if they contain any biologically active compounds. Sometimes, traditional medicine can give modern medicine clues as to where to find an active compound. For example, mankind has used willow bark to make medicine for thousands of years, dating back to ancient Egypt. However, it was not until the late 1800s that scientists and pharmaceutical companies purified and marketed the aspirin molecule, acetylsalicylic acid, for human use.

Occasionally, drugs developed for one use have unforeseen effects that allow usage in other, unrelated ways. For example, scientists originally developed the drug minoxidil (Rogaine) to treat high blood pressure. When tested on humans, researchers noticed that individuals taking the drug would grow new hair. Eventually the pharmaceutical company marketed the drug to men and women with baldness to restore lost hair.

A pharmaceutical chemist's career may involve detective work, experimentation, and drug development, all with the goal of making human beings healthier.

## Section Summary

Matter is anything that occupies space and has mass. It is comprised of elements. All of the 98 elements that occur naturally have unique qualities that allow them to combine in various ways to create molecules, which in turn combine to form cells, tissues, organ systems, and organisms. Atoms, which consist of protons, neutrons, and electrons, are the smallest units of an element that retain all of the properties of that element. Electrons can transfer, share, or cause charge disparities between atoms to create bonds, including ionic, covalent, and hydrogen bonds, as well as van der Waals interactions.

## Visual Connection Questions

**Exercise:**

**Problem:**

[link] How many neutrons do carbon-12 and carbon-13 have, respectively?

---

**Solution:**

[link] Carbon-12 has six neutrons. Carbon-13 has seven neutrons.

**Exercise:**

**Problem:**

[link] An atom may give, take, or share electrons with another atom to achieve a full valence shell, the most stable electron configuration. Looking at this figure, how many electrons do elements in group 1 need to lose in order to achieve a stable electron configuration? How many electrons do elements in groups 14 and 17 need to gain to achieve a stable configuration?

---

**Solution:**

[link] Elements in group 1 need to lose one electron to achieve a stable electron configuration. Elements in groups 14 and 17 need to gain four and one electrons, respectively, to achieve a stable configuration.

## Review Questions

**Exercise:**

**Problem:**

If xenon has an atomic number of 54 and a mass number of 108, how many neutrons does it have?

a. 54
b. 27
c. 100
d. 108

---

**Solution:**

A

**Exercise:**

**Problem:**

Atoms that vary in the number of neutrons found in their nuclei are called _____.

a. ions
b. neutrons
c. neutral atoms
d. isotopes

---

**Solution:**

D

**Exercise:**

**Problem:**

Potassium has an atomic number of 19. What is its electron configuration?

a. shells 1 and 2 are full, and shell 3 has nine electrons
b. shells 1, 2 and 3 are full and shell 4 has three electrons
c. shells 1, 2 and 3 are full and shell 4 has one electron
d. shells 1, 2 and 3 are full and no other electrons are present

---

**Solution:**

C

**Exercise:**

**Problem:** Which type of bond represents a weak chemical bond?

a. hydrogen bond
b. atomic bond
c. covalent bond
d. nonpolar covalent bond

---

**Solution:**

A

## Critical Thinking Questions

**Exercise:**

**Problem:** What makes ionic bonds different from covalent bonds?

---

**Solution:**

Ionic bonds are created between ions. The electrons are not shared between the atoms, but rather are associated more with one ion than the other. Ionic bonds are strong bonds, but are weaker than covalent bonds, meaning it takes less energy to break an ionic bond compared with a covalent one.

**Exercise:**

**Problem:**

Why are hydrogen bonds and van der Waals interactions necessary for cells?

---

**Solution:**

Hydrogen bonds and van der Waals interactions form weak associations between different molecules or within different regions of the same molecule. They provide the structure and shape necessary for proteins and DNA within cells so that they function properly.

## Glossary

anion
: negative ion that is formed by an atom gaining one or more electrons

atom
: the smallest unit of matter that retains all of the chemical properties of an element

atomic mass
: calculated mean of the mass number for an element’s isotopes

atomic number
: total number of protons in an atom

balanced chemical equation
: statement of a chemical reaction with the number of each type of atom equalized for both the products and reactants

cation
: positive ion that is formed by an atom losing one or more electrons

chemical bond
: interaction between two or more of the same or different atoms that results in forming molecules

chemical reaction
: process leading to rearranging atoms in molecules

chemical reactivity
: the ability to combine and to chemically bond with each other

compound
: substance composed of molecules consisting of atoms of at least two different elements

covalent bond
: type of strong bond formed between two atoms of the same or different elements; forms when electrons are shared between atoms

electrolyte
: ion necessary for nerve impulse conduction, muscle contractions, and water balance

electron
: negatively charged subatomic particle that resides outside of the nucleus in the electron orbital; lacks functional mass and has a negative charge of –1 unit

electron configuration
: arrangement of electrons in an atom’s electron shell (for example, $1s^2 2s^2 2p^6$)

electron orbital
: how electrons are spatially distributed surrounding the nucleus; the area where we are most likely to find an electron

electron transfer
: movement of electrons from one element to another; important in creating ionic bonds

electronegativity
: ability of some elements to attract electrons (often of hydrogen atoms), acquiring partial negative charges in molecules and creating partial positive charges on the hydrogen atoms

element
: one of 118 unique substances that cannot break down into smaller substances; each element has unique properties and a specified number of protons

equilibrium
: steady state of relative reactant and product concentration in reversible chemical reactions in a closed system

hydrogen bond
: weak bond between slightly positively charged hydrogen atoms and slightly negatively charged atoms in other molecules

inert gas
: (also, noble gas) element with filled outer electron shell that is unreactive with other atoms

ion
: atom or chemical group that does not contain equal numbers of protons and electrons

ionic bond
: chemical bond that forms between ions with opposite charges (cations and anions)

irreversible chemical reaction
: chemical reaction where reactants proceed unidirectionally to form products

isotope
: one or more forms of an element that have different numbers of neutrons

law of mass action
: chemical law stating that the rate of a reaction is proportional to the concentration of the reacting substances

mass number
: total number of protons and neutrons in an atom

matter
: anything that has mass and occupies space

molecule
: two or more atoms chemically bonded together

neutron
: uncharged particle that resides in an atom's nucleus; has a mass of one amu

noble gas
: see inert gas

nonpolar covalent bond
: type of covalent bond that forms between atoms when electrons are shared equally between them

nucleus
: core of an atom; contains protons and neutrons

octet rule
: rule that atoms are most stable when they hold eight electrons in their outermost shells

orbital
: region surrounding the nucleus; contains electrons

periodic table

organizational chart of elements indicating each element's atomic number and atomic mass; provides key information about the elements' properties

polar covalent bond
: type of covalent bond that forms as a result of unequal electron sharing, resulting in creating slightly positive and negative charged molecule regions

product
: molecule that is result of chemical reaction

proton
: positively charged particle that resides in the atom's nucleus; has a mass of one amu and a charge of +1

radioisotope
: isotope that emits radiation comprised of subatomic particles to form more stable elements

reactant
: molecule that takes part in a chemical reaction

reversible chemical reaction
: chemical reaction that functions bidirectionally, where products may turn into reactants if their concentration is great enough

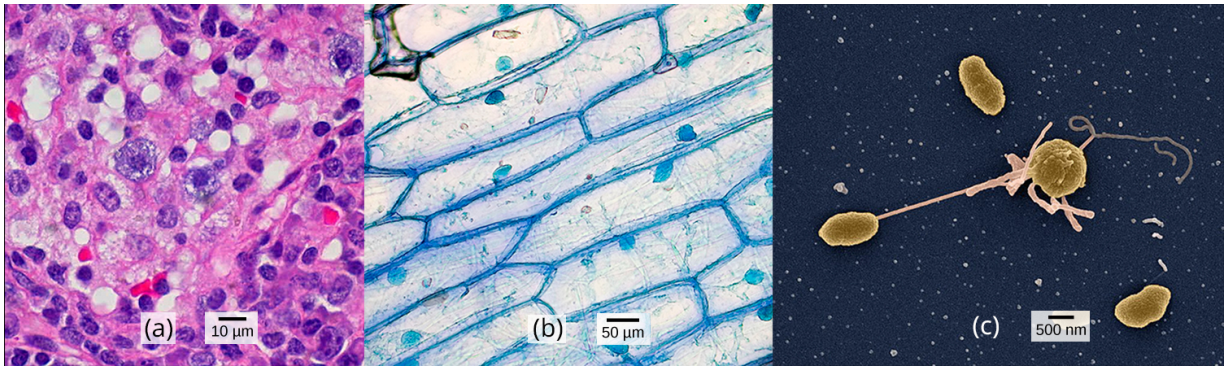
valence shell
: outermost shell of an atom

van der Waals interaction
: very weak interaction between molecules due to temporary charges attracting atoms that are very close together

Introduction
class="introduction"

(a) Nasal sinus cells (viewed with a light microscope), (b) onion cells (viewed with a light microscope), and (c) *Vibrio tasmaniensis* bacterial cells (seen through a scanning electron microscope) are from very different organisms, yet all share certain basic cell structure characteristics. (credit a: modification of work by Ed Uthman, MD; credit b: modification of work by Umberto Salvagnin; credit c: modification of work by

Anthony D'Onofrio, William H. Fowle, Eric J. Stewart, and Kim Lewis of the Lewis Lab at Northeastern University; scale-bar data from Matt Russell)




Close your eyes and picture a brick wall. What is the wall's basic building block? It is a single brick. Like a brick wall, cells are the building blocks that make up your body.

Your body has many kinds of cells, each specialized for a specific purpose. Just as we use a variety of materials to build a home, the human body is constructed from many cell types. For example, epithelial cells protect the body's surface and cover the organs and body cavities within. Bone cells help to support and protect the body. Immune system cells fight invading bacteria. Additionally, blood and blood cells carry nutrients and oxygen throughout the body while removing carbon dioxide. Each of these cell types plays a vital role during the body's growth, development, and day-to-day maintenance. In spite of their enormous variety, however, cells from all

organisms—even ones as diverse as bacteria, onion, and human—share certain fundamental characteristics.

Studying Cells
By the end of this section, you will be able to do the following:

- Describe the role of cells in organisms
- Compare and contrast light microscopy and electron microscopy
- Summarize cell theory

A cell is the smallest unit of a living thing. Whether comprised of one cell (like bacteria) or many cells (like a human), we call it an organism. Thus, cells are the basic building blocks of all organisms.

Several cells of one kind that interconnect with each other and perform a shared function form tissues. These tissues combine to form an organ (your stomach, heart, or brain), and several organs comprise an organ system (such as the digestive system, circulatory system, or nervous system). Several systems that function together form an organism (like a human being). Here, we will examine the structure and function of cells.

There are many types of cells, which scientists group into one of two broad categories: prokaryotic and eukaryotic. For example, we classify both animal and plant cells as eukaryotic cells; whereas, we classify bacterial cells as prokaryotic. Before discussing the criteria for determining whether a cell is prokaryotic or eukaryotic, we will first examine how biologists study cells.

## Microscopy

Cells vary in size. With few exceptions, we cannot see individual cells with the naked eye, so scientists use microscopes (micro- = “small”; -scope = “to look at”) to study them. A **microscope** is an instrument that magnifies an object. We photograph most cells with a microscope, so we can call these images micrographs.

The optics of a microscope’s lenses change the image orientation that the user sees. A specimen that is right-side up and facing right on the microscope slide will appear upside-down and facing left when one views through a microscope, and vice versa. Similarly, if one moves the slide left

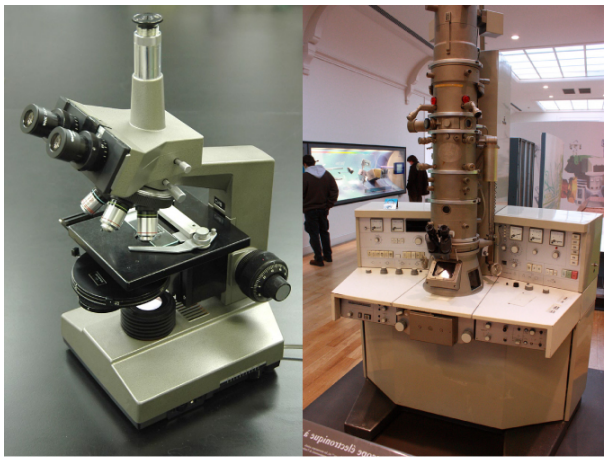
while looking through the microscope, it will appear to move right, and if one moves it down, it will seem to move up. This occurs because microscopes use two sets of lenses to magnify the image. Because of the manner by which light travels through the lenses, this two lens system produces an inverted image (binocular, or dissecting microscopes, work in a similar manner, but include an additional magnification system that makes the final image appear to be upright).

## Light Microscopes

To give you a sense of cell size, a typical human red blood cell is about eight millionths of a meter or eight micrometers (abbreviated as eight μm) in diameter. A pin head is about two thousandths of a meter (two mm) in diameter. That means about 250 red blood cells could fit on a pinhead.

Most student microscopes are **light microscopes** ([link]**a**). Visible light passes and bends through the lens system to enable the user to see the specimen. Light microscopes are advantageous for viewing living organisms, but since individual cells are generally transparent, their components are not distinguishable unless they are colored with special stains. Staining, however, usually kills the cells.

Light microscopes that undergraduates commonly use in the laboratory magnify up to approximately 400 times. Two parameters that are important in microscopy are magnification and resolving power. Magnification is the process of enlarging an object in appearance. Resolving power is the microscope's ability to distinguish two adjacent structures as separate: the higher the resolution, the better the image's clarity and detail. When one uses oil immersion lenses to study small objects, magnification usually increases to 1,000 times. In order to gain a better understanding of cellular structure and function, scientists typically use electron microscopes.



(a) (b)

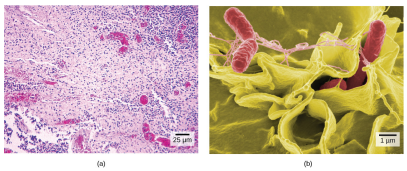
(a) Most light microscopes in a college biology lab can magnify cells up to approximately 400 times and have a resolution of about 200 nanometers. (b) Electron microscopes provide a much higher magnification, 100,000x, and a have a resolution of 50 picometers. (credit a: modification of work by "GcG"/Wikimedia Commons; credit b: modification of work by Evan Bench)

## Electron Microscopes

In contrast to light microscopes, **electron microscopes** ([link]**b**) use a beam of electrons instead of a beam of light. Not only does this allow for higher magnification and, thus, more detail ([link]), it also provides higher resolving power. The method to prepare the specimen for viewing with an electron microscope kills the specimen. Electrons have short wavelengths

(shorter than photons) that move best in a vacuum, so we cannot view living cells with an electron microscope.

In a scanning electron microscope, a beam of electrons moves back and forth across a cell's surface, creating details of cell surface characteristics. In a transmission electron microscope, the electron beam penetrates the cell and provides details of a cell's internal structures. As you might imagine, electron microscopes are significantly more bulky and expensive than light microscopes.




(a) These *Salmonella* bacteria appear as tiny purple dots when viewed with a light microscope. (b) This scanning electron microscope micrograph shows *Salmonella* bacteria (in red) invading human cells (yellow). Even though subfigure (b) shows a different *Salmonella* specimen than subfigure (a), you can still observe the

comparative increase in magnification and detail. (credit a: modification of work by CDC/Armed Forces Institute of Pathology, Charles N. Farmer, Rocky Mountain Laboratories; credit b: modification of work by NIAID, NIH; scale-bar data from Matt Russell)

**Note:**
Link to Learning
For another perspective on cell size, try the HowBig interactive at this site.

## Cell Theory

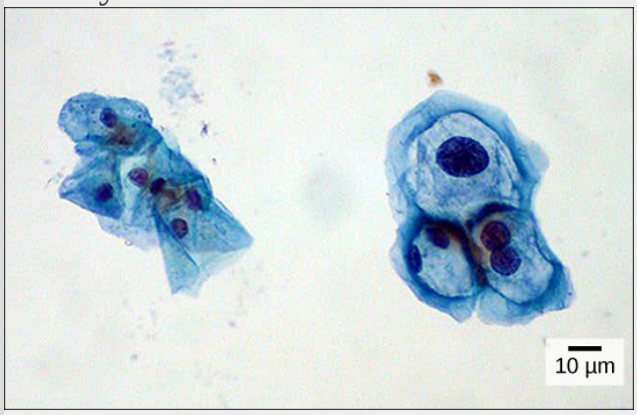
The microscopes we use today are far more complex than those that Dutch shopkeeper Antony van Leeuwenhoek, used in the 1600s. Skilled in crafting lenses, van Leeuwenhoek observed the movements of single-celled organisms, which he collectively termed “animalcules.”

In the 1665 publication *Micrographia*, experimental scientist Robert Hooke coined the term “cell” for the box-like structures he observed when viewing cork tissue through a lens. In the 1670s, van Leeuwenhoek discovered bacteria and protozoa. Later advances in lenses, microscope construction,

and staining techniques enabled other scientists to see some components inside cells.

By the late 1830s, botanist Matthias Schleiden and zoologist Theodor Schwann were studying tissues and proposed the **unified cell theory**, which states that one or more cells comprise all living things, the cell is the basic unit of life, and new cells arise from existing cells. Rudolf Virchow later made important contributions to this theory.

**Note:**
Career Connection
**Cytotechnologist**
Have you ever heard of a medical test called a Pap smear ([link])? In this test, a doctor takes a small sample of cells from the patient's uterine cervix and sends it to a medical lab where a cytotechnologist stains the cells and examines them for any changes that could indicate cervical cancer or a microbial infection.
Cytotechnologists (cyto- = “cell”) are professionals who study cells via microscopic examinations and other laboratory tests. They are trained to determine which cellular changes are within normal limits and which are abnormal. Their focus is not limited to cervical cells. They study cellular specimens that come from all organs. When they notice abnormalities, they consult a pathologist, a medical doctor who interprets and diagnoses changes that disease in body tissue and fluids cause.
Cytotechnologists play a vital role in saving people’s lives. When doctors discover abnormalities early, a patient’s treatment can begin sooner, which usually increases the chances of a successful outcome.



These uterine cervix cells, viewed through a light microscope, are from a Pap smear. Normal cells are on the left. The cells on the right are infected with human papillomavirus (HPV). Notice that the infected cells are larger. Also, two of these cells each have two nuclei instead of one, the normal number. (credit: modification of work by Ed Uthman, MD; scale-bar data from Matt Russell)

## Section Summary

A cell is the smallest unit of life. Most cells are so tiny that we cannot see them with the naked eye. Therefore, scientists use microscopes to study cells. Electron microscopes provide higher magnification, higher resolution, and more detail than light microscopes. The unified cell theory states that one or more cells comprise all organisms, the cell is the basic unit of life, and new cells arise from existing cells.

## Review Questions

**Exercise:**

**Problem:**

When viewing a specimen through a light microscope, scientists use _____ to distinguish the individual components of cells.

a. a beam of electrons

b. radioactive isotopes
c. special stains
d. high temperatures

---

**Solution:**

C

**Exercise:**

**Problem:** The _____ is the basic unit of life.

a. organism
b. cell
c. tissue
d. organ

---

**Solution:**

B

## Critical Thinking Questions

**Exercise:**

**Problem:**

In your everyday life, you have probably noticed that certain instruments are ideal for certain situations. For example, you would use a spoon rather than a fork to eat soup because a spoon is shaped for scooping, while soup would slip between the tines of a fork. The use of ideal instruments also applies in science. In what situation(s) would the use of a light microscope be ideal, and why?

---

**Solution:**

A light microscope would be ideal when viewing a small living organism, especially when the cell has been stained to reveal details.

**Exercise:**

**Problem:**

In what situation(s) would the use of a scanning electron microscope be ideal, and why?

---

**Solution:**

A scanning electron microscope would be ideal when you want to view the minute details of a cell's surface, because its beam of electrons moves back and forth over the surface to convey the image.

**Exercise:**

**Problem:**

In what situation(s) would a transmission electron microscope be ideal, and why?

---

**Solution:**

A transmission electron microscope would be ideal for viewing the cell's internal structures, because many of the internal structures have membranes that are not visible by the light microscope.

**Exercise:**

**Problem:**

What are the advantages and disadvantages of each of these types of microscopes?

---

**Solution:**

The advantages of light microscopes are that they are easily obtained, and the light beam does not kill the cells. However, typical light microscopes are somewhat limited in the amount of detail they can

reveal. Electron microscopes are ideal because you can view intricate details, but they are bulky and costly, and preparation for the microscopic examination kills the specimen.

**Exercise:**

**Problem:**

Explain how the formation of an adult human follows the cell theory.

---

**Solution:**

The cell theory states:

1. All living things are made of cells.;
2. Cells are the most basic unit of life.;
3. New cells arise from existing cells.

All humans are multicellular organisms whose smallest building blocks are cells. Adult humans begin with the fusion of a male gamete cell with a female gamete cell to form a fertilized egg (single cell). That cell then divides into two cells, which each divides into two more cells, and so forth until all the cells of a human embryo are made. As the embryo passes through all the developmental stages to make an adult human, the cells that are added arise from division of existing cells.

## Glossary

cell theory
: see unified cell theory

electron microscope
: an instrument that magnifies an object using an electron beam that passes and bends through a lens system to visualize a specimen

light microscope

an instrument that magnifies an object using a beam of visible light that passes and bends through a lens system to visualize a specimen

microscope
: an instrument that magnifies an object

unified cell theory
: a biological concept that states that one or more cells comprise all organisms; the cell is the basic unit of life; and new cells arise from existing cells

Measurements and the Metric System

| Measurements and the Metric System | | | | |
|---|---|---|---|---|
| **Measurement** | **Unit** | **Abbreviation** | **Metric Equivalent** | **Approximate Standard Equivalent** |
| Length | nanometer | nm | 1 nm = $10^{-9}$ m | 1 mm = 0.039 inch<br>1 cm = 0.394 inch<br>1 m = 39.37 inches<br>1 m = 3.28 feet<br>1 m = 1.093 yards<br>1 km = 0.621 miles |
| | micrometer | µm | 1 µm = $10^{-6}$ m | |
| | millimeter | mm | 1 mm = 0.001 m | |
| | centimeter | cm | 1 cm = 0.01 m | |
| | meter | m | 1 m = 100 cm<br>1 m = 1000 mm | |
| | kilometer | km | 1 km = 1000 m | |
| Mass | microgram | µg | 1 µg = $10^{-6}$ g | 1 g = 0.035 ounce<br>1 kg = 2.205 pounds |
| | milligram | mg | 1 mg = $10^{-3}$ g | |
| | gram | g | 1 g = 1000 mg | |

| **Measurements and the Metric System** | | | | |
|---|---|---|---|---|
| **Measurement** | **Unit** | **Abbreviation** | **Metric Equivalent** | **Approximate Standard Equivalent** |
| | kilogram | kg | 1 kg = 1000 g | |
| Volume | microliter | µl | 1 µl = $10^{-6}$ l | 1 ml = 0.034 fluid ounce<br>1 l = 1.057 quarts<br>1 kl = 264.172 gallons |
| | milliliter | ml | 1 ml = $10^{-3}$ l | |
| | liter | l | 1 l = 1000 ml | |
| | kiloliter | kl | 1 kl = 1000 l | |
| Area | square centimeter | $cm^2$ | 1 $cm^2$ = 100 $mm^2$ | 1 $cm^2$ = 0.155 square inch<br>1 $m^2$ = 10.764 square feet<br>1 $m^2$ = 1.196 square yards<br>1 ha = 2.471 acres |
| | square meter | $m^2$ | 1 $m^2$ = 10,000 $cm^2$ | |
| | hectare | ha | 1 ha = 10,000 $m^2$ | |
| Temperature | Celsius | °C | — | 1 °C = 5/9 × (°F − 32) |